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SUMMARY OF THE GEOLOGY OF THE BEARTOOTH MOUNTAINS, MONTANA[1]

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OUTLINE

LOCATION AND EXTENT OF THE RANGE
SALIENT TOPOGRAPHIC FEATURES
- The Plains-ward Front
- The Sub-summit Plateau
- The Summit Plateau

STRATIGRAPHY
- The Pre-Cambrian Core
- Sedimentary Formations
- Tertiary Igneous Rocks
- Terrace Gravels
- Glacial Drift

STRUCTURE
- General Form of the Range
- The Beartooth Overthrust
- The Clark Fork Fault (?)

HISTORY OF THE RANGE
- Antecedent Conditions
- Early Tertiary Orogeny
- Epochs of Peneplanation
- Quaternary Events

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LOCATION AND EXTENT OF THE RANGE

The Beartooth Mountains are in southern Montana and northwestern Wyoming, where they form the front range of the Rocky Mountains. The range has the approximate form of a broad, much elongated, slightly curved oval which extends southeasterly from Yellowstone Valley above Livingston to the canyon of the Clark Fork of Yellowstone River, about 30 miles northwest of Cody, Wyoming (Fig. 1). It is about 80 miles long and has a maximum width of about 30 miles south of its central portion, northeast of the northeast corner of Yellowstone Park.

The boundary between the range and the Great Plains is sharply marked (Figs. 2 and 3) but the boundary on the southwest is much less definite. South of the state line the Clark Fork is taken commonly as the line of demarcation between the Beartooth Mountains and the Absaroka Range to the west. In Montana the two ranges merge more or less, which makes it difficult to draw a sharp natural boundary between them. For this discussion the boundary is taken mainly along the divide between the streams that flow south and west to Yellowstone River and those that pursue a northerly course across the greater portion of the Beartooth Mountains to the same river far beyond the front of the range. Inasmuch as this boundary roughly follows the structural limits of the range, it is less arbitrarily chosen than may appear from this statement.

The range lies wholly within the drainage system of Yellowstone River. With the exception of Soda Butte Creek and a few other small creeks that flow into the northeastern part of Yellowstone Park, all of the streams flow northeasterly from the plains-ward front of the range across the bordering plains for many miles before uniting with the trunk stream. The main streams are permanent, even in seasons of excessive drought, as they receive an abundant and constant water supply from numerous perpetual snow fields, several small glaciers, and a multitude of lakes that are scattered throughout the range.

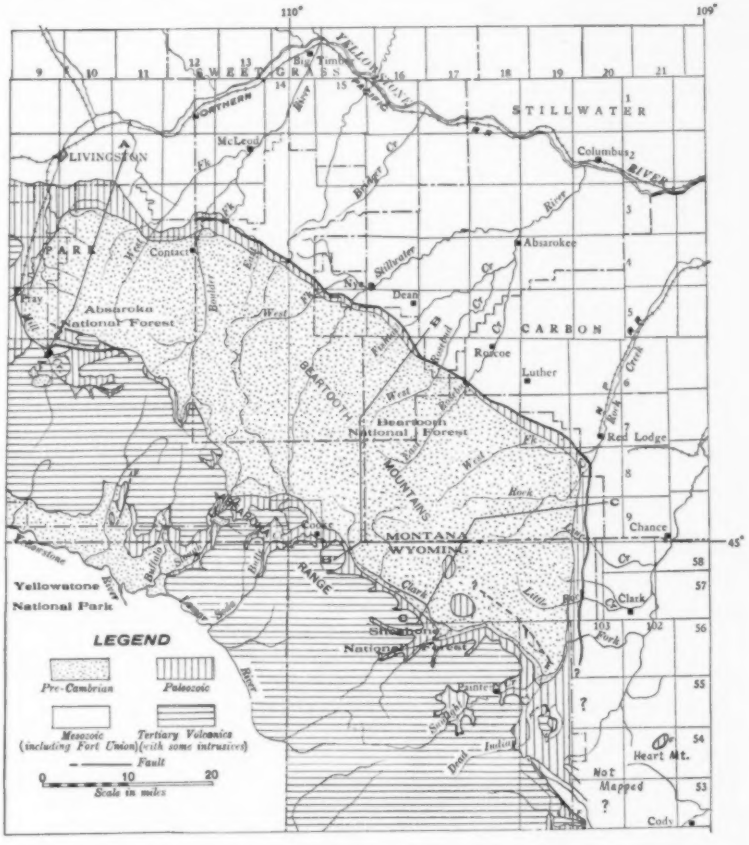

FIG. 1.—Sketch geologic map of the Beartooth Mountains and environs. Based in part on publications of the United States Geological Survey. Geology northwest of Cody after C. L. Dake. Geology west and south of Livingston somewhat generalized.

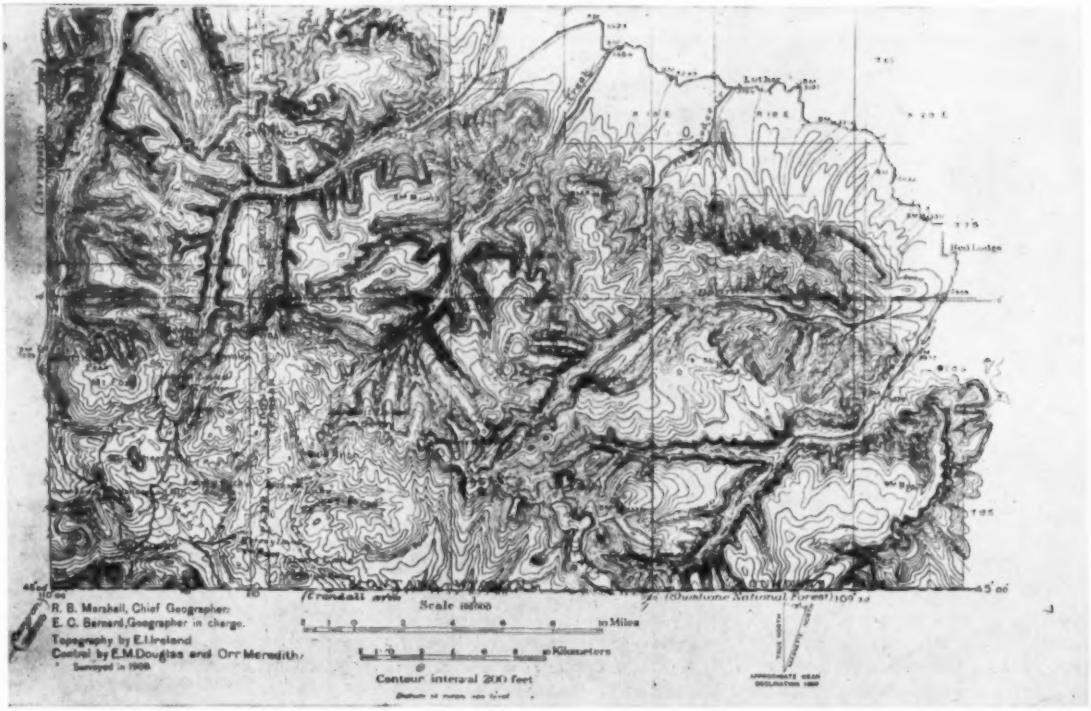

FIG. 2.—Topographic map of the central part of the Beartooth Range. Note the abrupt plains-ward front, extensive flattish areas of the sub-summit plateau, summit plateau remnants between 109°30′ and 109°40′, glaciated area on southwest slope, and the canyon-like valleys on the northeast slope.

SALIENT TOPOGRAPHIC FEATURES

The plains-ward front.—The Beartooth Range rises abruptly to a height of a few thousand feet above the Great Plains on the northeast. The 6,000-foot contour almost everywhere follows the base of the range, and the plains-ward crest has an elevation of 9,000 to 10,000 feet. In the southern part the frontal slope is uncommonly steep, but to the north it is neither so steep nor so uniform nor everywhere so sharply separated from the bordering plains.

The sub-summit plateau.—The remarkably even outline of the crest for considerable distances, especially in the southern half of the range, is an impressive feature (Fig. 3). It marks the plains-ward rim of a broad flattish plateau that extends along the eastern portion of the range for most of its length. This extensive surface is herewith designated, from its form and topographic position, the "sub-summit plateau." It consists of a series of gently undulating upland flats, each containing several square miles, that are the remnants of a once continuous erosional plain (Fig. 2). The largest tracts are about 10 miles wide and have an area of 10 to 20 square miles. Extensive portions of some of these plateau remnants are strikingly flat (Fig. 4).

In its longest dimension, parallel to the axis of the range, this plateau varies in altitude from slightly less than 10,000 feet, in the vicinity of Boulder River, to more than 11,000 feet in the central portion, then drops a few hundred feet toward its southern extremity. Its surface rises gradually toward the interior of the range, but becomes increasingly steep toward the main axial divide.

Sharp valleys 3,000 to 4,000 or more feet deep have been carved in this plateau by the several northeasterly flowing streams and their numerous tributaries. The dissection is least advanced in the southern half of the range and has progressed farthest in the northwestern portion, but even here the old surface is partially preserved in flattish tracts of considerable size. East Boulder and West Boulder plateaus, which are shown on the topographic map of the Livingston, Montana, quadrangle, are fairly typical remnants, but the best examples are in the south-central part of the range, just north of the Wyoming boundary (Figs. 2 and 4).

FIG. 3.—The plains-ward front of the Beartooth Range west of West Rosebud Creek. The elevation at the base is about 6,000 feet and at the summit about 10,000 feet. The even crest marks the rim of the sub-summit plateau, which is notched by cirques.

FIG. 4.—A portion of the sub-summit plateau showing its remarkable flatness over large areas. The altitude is about 10,000 feet. The rocks are pre-Cambrian crystallines. Silver Run Plateau, southwest of Red Lodge, in the foreground, with Line Creek Plateau to the south beyond Rock Creek.

The summit plateau.—The axial portion of the range is characterized by two distinctly opposing features: its extreme ruggedness, and the flattish summits of many of the dominant peaks (Fig. 5). The highest peaks and ridges of this rugged district in the south-central part of the range exhibit remarkably even-crested summits when viewed from any direction. The most extensive remnant of

FIG. 5.—Remnants of the summit peneplain along the main divide at the head of Rock Creek. Elevation of the even crests is about 12,400 feet. Looking southwest from Silver Run Plateau.

the summit plateau, which is called the Beartooth Plateau,[1] exists just north of the Wyoming boundary. It is a narrow, deeply notched plateau with an area of several square miles, which coincides with the axis of the range for about 12 miles (Fig. 2). Its rim almost everywhere overlooks very steep slopes or sheer precipices, most of which are from 1,000 to more than 1,500 feet high. The

[1] The name Beartooth Plateau has been used by some to mean the sub-summit plateau along the eastern front of the range, or the glaciated plateau on the southwestern slope. The writer follows the usage of the term on the published topographic map of the Beartooth National Forest, where the name is restricted to the summit plateau.

elevation of this plateau is approximately 12,000 to 12,400 feet, or about 1,500 to 2,000 feet above the general surface of the sub-summit plateau. As observed from an altitude of 12,200 feet in the vicinity of Granite Peak it appears to have a southwesterly dip of about 5° (Fig. 6).

FIG. 6.—The summit peneplain southeast of East Rosebud Valley. The elevation is about 12,400 feet. The rocks are pre-Cambrian crystallines. Looking southeast from the vicinity of Granite Peak.

STRATIGRAPHY[1]

The pre-Cambrian core.—The main mass of the range consists chiefly of pre-Cambrian granite and granite-gneiss, with subordinate amounts of basic gneisses and schists. A considerable mass of anorthosite-gneiss exists on the east side of Boulder Valley, and extends southeast for an unknown distance.[2] Numerous basic intrusions, mainly dikes and small stocks, partly of pre-Cambrian age and in part possibly much younger, invade this crystalline core

[1] The areal geology of the northwestern portion of the range is shown by the Livingston, Montana, folio (No. 1), and that of the southwestern slope south of the state line on the Crandall sheet of the Absaroka, Wyoming, folio (No. 52).

[2] C. H. Clapp, oral communication.

in many places. Coarse pegmatite dikes are fairly common in the granite and gneiss. A unique feature is a large dike of pyroxenite that extends from Boulder River, below Contact, southeast beyond the head of Little Rocky Creek, southwest of Dean, and contains a large tabular deposit of high-grade chromite.[1]

No sedimentary formations of pre-Cambrian age have been discovered anywhere in this region.

Sedimentary formations.—Sedimentary formations are restricted to the flanks of the range. The indurated strata range in age from middle Cambrian to late Cretaceous or Paleocene. All the Paleozoic systems, except the Silurian which is absent, are represented by extensive deposits of limestone and dolomite with subordinate amounts of more or less calcareous shale and sandstone. The entire sequence is present along the eastern and northern base of the range, but erosion has removed most of the upper Paleozoics on the southwest slope north of the Wyoming boundary. Mesozoic formations are present only along the plains-ward front of the range and in the adjacent plains. All the systems are present. They consist preponderantly of alternating sandstone and shale with some limestone, gypsum, and coal. The upper part of the sequence in the northern part of the area is composed mainly of volcanic materials (Livingston formation). In Carbon County a thick series (Fort Union) of sandstone, shale, and coal lies with apparent conformity upon the youngest beds of undoubted Mesozoic age. Farther south along the mountain front a conspicuous conglomerate may be of later age.

The maximum thickness of the sedimentary formations on the east side of the Beartooth Range is approximately 18,000 feet. This is exclusive of the Livingston tuffaceous sandstones and agglomerates which in places are more than 5,000 feet thick. The Paleozoic systems have a total thickness between 3,500 and 4,000 feet, the undoubted Mesozoic systems about 6,000 feet, and the strata included in the Fort Union formation approximately 8,500 feet.[2]

[1] L. G. Westgate, "Deposits of Chromite in Stillwater and Sweetgrass Counties, Montana," *U.S. Geol. Survey Bull. 725-A*, 1921, pp. 67–84.

[2] E. G. Woodruff, "The Red Lodge Coal Field, Montana," *U.S. Geol. Survey Bull. 341*, 1908, Pt. II, p. 92.

The thickness of the individual formations and their main characteristics are shown in Table I. Many of the thickness values have

TABLE I

FORMATIONS IN THE BEARTOOTH MOUNTAINS AND ADJACENT GREAT PLAINS

Age	Formation	Approximate Thickness	Dominant Characteristics
		Feet	
Quaternary		?	Glacial drift, stream gravels, talus, and landslides
Tertiary		?	Andesitic breccias and lavas
Tertiary (?)	Fort Union (Lance (?) in lower part)	8,500	Yellowish sandstone and shale with several beds of workable coal; contains leaves and fresh-water shells
Tertiary (?) and Cretaceous	Livingston	3,000–5,000	Brownish and greenish andesitic sandstone and shale, with a thick member of andesitic agglomerate; lower beds are leaf-bearing
Cretaceous	Montana group: Bearpaw	125	Dark-gray clayey shale with scattered concretions and a few thin sandstones; marine invertebrate fossils
	Judith River	375	Soft, gray to yellowish sandstone and sandy shale with some lignitic beds; fresh- and brackish-water shells
	Claggett	435	Gray sandstone and sandy shale; marine and brackish-water invertebrates
	Eagle	200–300	Gray to white sandstone, thin- to massive-bedded, with sandy and carbonaceous shale; contains workable coal; marine fossils in lower part
	Colorado	2,000–3,700*	Dark-gray clayey shale with some intercalated sandstone and scattered calcareous concretions; marine fossils
Comanchean	Kootenai	300–500	Buff coarse-grained to conglomeratic sandstone, and purple to maroon shale
Comanchean and Jurassic (?)	Morrison	150	Dark-gray to greenish-gray sandstone and shale
Jurassic	Ellis	350–450	Greenish and reddish sandy shale, gray sandstone, and gray limestone; becomes sandy limestone to northwest; abundant marine fossils
Triassic	Chugwater	0–700	Red sandstone and shale with beds of gypsum
Permian (?)	Phosphoria	400	Gray quartzite and sandstone, chert, reddish shale, and impure limestone; marine fossils
Penn. and Miss.	Quadrant		
Mississippian	Madison	1,500	Light- to dark-gray, blue-gray and brown limestone in thin to thick beds; chert nodules locally; abundant marine fossils
Devonian	Threeforks	100	Dark-gray, thin-bedded limestone alternating with dark shale; marine fossils locally
	Jefferson	425	Light- to dark-gray and brown fetid dolomite; commonly thin-bedded; marine fossils locally
Ordovician	Bighorn	435	Light-gray to buff cliff-making dolomite alternating with thin beds; few marine fossils
Cambrian	Gallatin	400	Interbedded limestone and shale, flat-pebble conglomerate, glauconitic and oolitic beds; marine fossils, as trilobites
	Flathead	400	Shale, thin sandstone, and thin limestone; basal conglomerate locally
Pre-Cambrian (Archean?)			Mainly granite, granite-gneiss, and mica schist; basic gneiss locally

* This thickness is doubtfully assigned to the Colorado near Livingston by W. R. Calvert, *U.S. Geol. Survey Bull. 471*, 1912, p. 387.

been obtained from the publications to which reference is made in the footnotes.[1]

[1] The data for the Montana group in this area have been obtained largely from C. A. Fisher, "Southern Extension of the Kootenai and Montana Coal-Bearing Formations in Northern Montana," *Econ. Geol.*, III (1908), pp. 93–96.

The Flathead formation (middle Cambrian) and the Gallatin formation (middle and upper Cambrian) cannot be readily subdivided in this part of the state into the several formations that constitute the Cambrian system in the Little Belt Mountains[1] and northwest along the Rocky Mountain Front. The Bighorn dolomite apparently marks in this range the northern-most extent of the Ordovician in Montana. Although the formation is a lithologic unit with no evidence of a break in it yet discovered on the northeast side of the range, "a conspicuous surface of disconformity, with a basal breccia" exists in it on the extreme southwest slope.[2] It may be noted further that the Devonian of Montana apparently does not extend many miles south of the Beartooth Range in Wyoming. Hence this range contains one of the most complete Paleozoic sections in the northern Rocky Mountains. The Madison limestone is the bold cliff-making limestone (Fig. 7) which is so conspicuous throughout the northern Rockies. The Quadrant formation in the northern part of the range is roughly equivalent to the Amsden and Tensleep formations in Clark Fork Canyon at the southern end of the range. D. D. Condit has recently differentiated the Phosphoria formation in this region, and has indicated its distribution along the east base of the range.[3]

A narrow belt of the Chugwater "Red Beds," presumably in the main of Triassic age, is present along the base of the range in northwestern Wyoming, but disappears a short distance north of the state line. The Chugwater and Quadrant formations are overlain respectively by the Sundance formation in Wyoming and the Ellis formation in Montana—two marine formations that are equivalent in the main and of middle to late Jurassic age.[4] They are composed chiefly of interbedded shale and limestone in proportions which vary from place to place. Between the mountain front and Clark Fork River in the plains, the Morrison and Kootenai

[1] W. H. Weed, "Geology of the Little Belt Mountains, Montana," *U.S. Geol. Survey Ann. Rept. XX*, 1900, Pt. 3, pp. 284–87.

[2] C. W. Tomlinson, "The Middle Paleozoic Stratigraphy of the Central Rocky Mountain Region," *Jour. Geol.*, XXV (1917), 35.

[3] *U.S. Geol. Survey*, Prof. Paper 120–F, Pl. IX, 1918.

[4] Charles Schuchert, *Bull. Geol. Soc. Am.*, XXIX (1918), 246.

(or the roughly equivalent Cloverly) formations, both in the main of Comanchean age, the Colorado shale, and the divisions of the Montana group, are exposed in several places. The Morrison and Cloverly formations crop out only in the southeastern part of the district, where they consist of varicolored clastics and thin limestones of non-marine origin. The Kootenai formation is present

FIG. 7.—Massive Madison limestone that forms a conspicuous ridge west of Red Lodge. The beds are overturned slightly to the east (right). Gravel-capped Fort Union strata beyond east base of the ridge.

along the base of the range east of Livingston, where it corresponds approximately to the Dakota formation, as delineated on the Livingston areal map (Folio No. 1). The Colorado shale is the typical thick deposit of marine shale, but with more interbedded sandstone than is common farther north in Montana. A succession of non-marine sandstones and marine shales similar to that of the Lake Basin district[1] to the northeast, constitutes the Montana

[1] E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey Bull. 691-D*, 1918, pp. 114–24.

group in Clark Fork Valley,[1] but the shales become distinctly more arenaceous and in part grade laterally into sandstone as the mountain front is approached. The Eagle formation contains workable coal in Clark Fork and Stillwater valleys.[2] Along the northern third of the range the Eagle is overlain by the thick tuffaceous beds of the Livingston formation, which apparently accumulated during the early Montana to Fort Union interval.[3] This formation consists of andesitic sandstones with a thick areally extensive lens of agglomerate as the middle portion.

The Lance formation has not been certainly identified in this region, and as typically developed on the Great Plains may be lacking. Detailed work in this part of the state will probably show that it is represented in the basal portion of the extraordinarily thick "Fort Union" section in Carbon County. Some of the tuffaceous sandstones in the upper part of the Livingston formation may be in part equivalent to the Lance.

The Fort Union formation occupies a broad area in the vicinity of Red Lodge and extends south along the mountain front toward the Wyoming line. It consists of a thick series of interbedded sandstone, shale, and clay, with numerous beds of coal in the middle portion. Several of these beds supply most of the coal produced in Carbon County. The entire formation is of continental origin.

Although the Fort Union formation in Montana is generally considered to be of early Eocene (Paleocene) age, there is a growing tendency to refer it with the Lance to the uppermost Cretaceous.[4] This is due in part to the apparent establishment of the Cretaceous age of the Lance by the discovery elsewhere of a member with a

[1] C. A. Fisher, *op. cit.*, pp. 77–99.

[2] Students of this region should note that the Laramie as shown on the Livingston areal map has been determined to be lower Montana, including the Eagle. See W. R. Calvert, *U.S. Geol. Survey Bull. 471*, 1912, pp. 386–89.

[3] R. W. Stone and W. R. Calvert, "Stratigraphic Relations of the Livingston Formation of Montana," *Econ. Geol.*, V (1910), 751–52.

[4] C. H. Clapp, "Cretaceous and Tertiary Continental Formations (of Central and Eastern Montana)," *Mont. Bur. of Mines and Metal. Bull. No. 4*, 1921, pp. 25–26.

W. D. Matthew, "Fossil Vertebrates and the Cretaceous-Tertiary Problem," *Am. Jour. Sci.*, 5th Ser., II (1921), 205–27.

Charles Schuchert, "Are the Lance and Fort Union Formations of Mesozoic Time?" *Science*, LIII (1921), 45–47.

marine Cretaceous fauna,[1] and the close relationship of the Lance and Fort Union formations. If the Lance is of Cretaceous age, the inclusion of the Fort Union in the Mesozoic is strongly supported by the lithologic similarity of the two formations, the homogeneity of the floras,[2] and the apparent lack of any pronounced hiatus in the Lance-Fort Union sequence. Moreover, upon the basis of recent studies of vertebrate remains in these and similar formations, the conclusion has been reached that the Fort Union belongs in the Cretaceous system.[3]

The Red Lodge district thus far has afforded no evidence bearing upon these phases of the problem. It is, however, a pertinent fact of considerable significance that the Fort Union of this region was involved in the first orogeny that deformed the underlying Mesozoic formations.

South of the Montana line within two miles of the mountain front is a line of hills formed of steeply tilted strata of a rather loosely cemented conglomerate which is composed mainly of well-rounded pebbles and cobbles of Paleozoic limestones. The age and relations of these beds have not been carefully determined, but from their position they seem to be either a part of the Fort Union or the marginal outcrops of the Wasatch of the Bighorn Basin. Although their lithology is more in accord with the published descriptions of the latter, their position and structure suggest that they may be a member of the Fort Union. They may possibly even be of intermediate age.

Another conglomerate, the Linley conglomerate, is present a short distance beyond the range, 10 miles northwest of Red Lodge, where it "lies with marked unconformity on tilted and eroded Fort Union beds."[4] It consists of about 300 feet (maximum) of sand and pebbles of igneous rocks from the crystalline core of the range,

[1] E. R. Lloyd and C. J. Hares, "The Cannonball Marine Member of the Lance Formation of North and South Dakota and Its Bearing on the Lance-Laramie Problem, *Jour. Geol.*, XXIII (1915), 253–57.

[2] F. H. Knowlton, "Are the Lance and Fort Union Formations of Mesozoic Time?" *Science*, LIII (1921), p. 307.

[3] W. D. Matthew, *op. cit.*

[4] W. R. Calvert, "Geology of the Upper Stillwater Basin, Stillwater and Carbon Counties, Montana," *U.S. Geol. Survey Bull. 641–G*, 1916, p. 203.

and a small amount of limestone. It is a local deposit, covering a few square miles, which is probably much younger than the conglomerate south of the state line.

Tertiary igneous rocks.—With the exception of the Livingston formation igneous materials of post-Cambrian age are not common in the Beartooth Mountains. Several dikes, sills, and stocks of Tertiary (?) age are present on the lower southwest slope in the Cooke mining district, and in the Haystack Peak area at the head of the main Boulder River.[1] On the east side of the range, south of Red Lodge, the Fort Union formation is invaded by a few narrow vertical dikes that are roughly parallel to the mountain front.[2] Some of the dikes and stocks within the pre-Cambrian core are probably of Tertiary age, but their extent remains to be determined.

The upper part of the imposing front of the adjacent Absaroka Range in northwestern Wyoming has been carved by the Clark Fork from more than 6,000 feet of volcanics that were ejected from the Crandall Basin volcano and associated vents during the Tertiary. The well-known landmarks of Pilot and Index peaks, which tower impressively above the southwest slope of the Beartooth Range, are sharply eroded from these formations. Although these volcanics do not now extend into the Beartooth Mountains, their great thickness and proximity indicate that their former eastward extent was much greater.

Terrace gravels.—Unconsolidated deposits of Tertiary and Quaternary age are widespread along the western margin of the Great Plains where they extend for many miles beyond the plainsward front of the Beartooth Mountains. The most common materials are stream gravels and bowlders of diverse constitution, which once probably formed an extensive piedmont plain. They have been worked over and over by the major streams and deposited in part at successively lower levels until now they mantle a series of broad terraces upon the truncated sedimentary formations along and between the principal valleys. Three or four of these terraces

[1] W. H. Emmons, "Geology of the Haystack Stock, Cowles, Park County, Montana," *Jour. Geol.*, XVI (1908), 193–229.

[2] N. H. Darton, "Coals of Carbon County, Montana," *U.S. Geol. Survey Bull. 316*, 1907, p. 186.

are commonly present, with the uppermost one several hundred feet above the present streams (Fig. 8).

Glacial drift.[1]—Glacial drift in the form of typical moraines and outwash gravels is present in most of the valleys on the east and northeast slopes of the range. This drift was deposited by fifteen systems of alpine glaciers, many of which contained numerous large tributaries. The outermost moraines commonly exist from 2 to 6 miles beyond the mountain front, but in a few valleys they are a

FIG. 8.—Terraces along West Fork of Rock Creek, southwest of Red Lodge

short distance within it. A few of the lateral moraines below the canyon mouths are huge ridges that attain heights of 500 to 1,000 feet above the valley floors (Fig. 9). Drift of two distinct epochs, probably corresponding to early and late Wisconsin, is clearly recognized in several valleys. An impressive characteristic of the recent drift is the abundance of large bowlders strewn over its surface. In some valleys the later glaciers advanced beyond the earlier ones, whereas in others the older lateral moraines extend a mile or two beyond the younger terminal moraines.

A considerable portion of the southwest slope was occupied by a large ice sheet which left an abundance of striated and polished

[1] A paper on the glaciation of the range is being prepared by the writer.

surfaces, countless perched bowlders, and extensive morainal deposits. The area thus glaciated is about 350 square miles between the base of the axial divide on the northeast and the front of the Absaroka Range on the southwest. An extraordinary feature of this glacier was the formation of several distinct valley lobes which passed into valleys sharply trenched athwart the axial divide, then descended these valleys to the plains beyond the eastern base of the range, where conspicuous moraines were formed.

FIG. 9.—The recent lateral moraine on the southeast side of East Rosebud Creek. Its height is about 600 feet.

STRUCTURE

General form of the range.—The Beartooth Range is structurally a broad asymmetric anticline that is in part strongly overturned toward the Great Plains and broken along its northeast limb by a huge fault (Fig. 10). The Paleozoic formations on the southwest slope commonly have low southwesterly dips whereas along the northeast flank they exhibit a variation from high easterly dips to overturned beds that are more than 70° beyond the vertical. Numerous minor faults and folds exist along this side of the range and in the adjacent plains.

The Beartooth overthrust.—The plains-ward front of the range is bounded throughout almost its entire length by the Beartooth

fault, which is an overthrust of considerable magnitude. West of Red Lodge the overturned Madison limestone on the west has been brought against the upper part of the Fort Union formation on the east side of the fault trace. Farther northwest, in the vicinity of West Rosebud Creek, the relations of the faulted formations are obscured by the widespread mantle of terrace gravel and glacial drift, but it appears that the pre-Cambrian crystallines abut

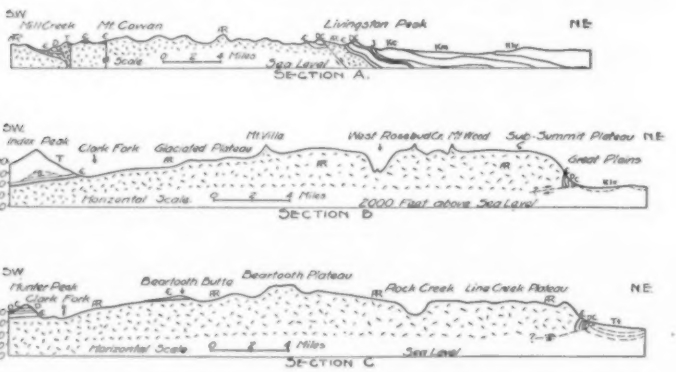

FIG. 10.—Geologic cross-sections of the Beartooth Mountains. Section A is a modification of section CDE of the Livingston folio. *AR*, Archean; *C*, Cambrian and Ordovician; *D*, Devonian; *C*, Carboniferous; *J*, Jurassic and Comanchean; *Kc*, Colorado; *Km*, Montana; *Klv*, Livingston; *Tf*, Fort Union; *T*, Tertiary volcanics and intrusives.

against, or overlie, the upper part of the Livingston formation or the lower part of the Fort Union formation.

Along the southeastern front of the range, between the state line and Clark Fork Canyon, the Beartooth fault becomes a zone of thrust faults that in places cause the pre-Cambrian granite to rest upon the Chugwater "Red Beds" (Triassic).[1] "At one point the Chugwater is dipping west (overturned) at angles as low as 20°, and passes under the granite. At another point, the Dakota (Cloverly) was also seen dipping west at a very flat angle, and clearly upside down. The evidence of overturning rested not only

[1] C. L. Dake, "The Heart Mountain Overthrust and Associated Structures in Park County, Wyoming," *Jour. Geol.*, XXVI (1918), 52–53.

on the succession of beds, but on ripple-marks and cross-bedding, and is beyond dispute."[1]

The maximum thickness of the formations displaced by this fault is not less than 10,000 feet, and in places may be considerably more. The actual fault plane has nowhere been observed, but it dips westward at an angle apparently higher than is characteristic of most other Rocky Mountain overthrusts. The strata east of the fault are in some places sharply flexed whereas in others they

FIG. 11.—The Beartooth fault zone southeast of Stillwater Valley. Vertical Madison limestone along the range front, with gently east-dipping Livingston beds on valley slope. Looking southeast.

dip gently away from the fault zone (Fig. 11). At Red Lodge the Fort Union formation dips 18° toward the mountain front, but in the intervening distance of 4 miles it becomes horizontal, then dips gently in the opposite direction as the fault is approached.

The Beartooth overthrust appears to be the northward extension of the Heart Mountain overthrust of northwestern Wyoming, which has been determined recently by Hewett to have an eastward thrust of not less than 28 miles.[2] If not the direct continuation of the Heart Mountain fault it was very probably formed during the

[1] C. L. Dake, letter to the writer, Feb. 13, 1921.

[2] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, XXVIII (1920), 536.

same orogenic epoch. Inasmuch as the fault plane is not exposed and remnants of overthrust beds, if ever present, have not been preserved beyond the eastern base of the range, the amount of horizontal displacement along the Beartooth front is indeterminable. In view of the enormous displacement at Heart Mountain beyond the southeastern end of this range, it is not improbable that the maximum displacement along the Beartooth fault plane was at least several miles, though this is not an absolute corollary.

FIG. 12.—The Clark Fork fault (?) along the southwest side of the range. Pre-Cambrian granite in the foreground, overlain by horizontal Cambrian in the distance. Range in background is of pre-Cambrian granite.

The Clark Fork fault (?).—The extreme southwest flank of the range, along the northeast side of Clark Fork Canyon, appears to be bounded by a considerable fault of the gravity (or "normal") type. A rapid reconnaissance trip in stormy weather permitted only a cursory inspection of the geology of this area, but the bold escarpment that here rises abruptly to the western rim of the subsummit plateau is strongly suggestive of a fault. The topographic evidence is well shown on the topographic maps,[1] although no fault

[1] Crandall, Wyoming, quadrangle and the advance sheet of Part of the Shoshone National Forest, Wyoming.

is indicated on the areal map of the Crandall quadrangle (Folio 52). Furthermore, the pre-Cambrian granite of which the escarpment is composed rises abruptly more than 2,000 feet above Cambrian strata at its base, which are apparently horizontal, or at most only slightly warped (Fig. 12). This escarpment trends northwest and disappears southwest of Beartooth Butte in the crystalline rocks of the sub-summit plateau. The maximum vertical displacement of this fault may be several thousand feet, as all the Paleozoic formations, and an unknown thickness of the pre-Cambrian rocks, have been eroded from the summit of the range.

HISTORY OF THE RANGE

Antecedent conditions.—The Paleozoic and Mesozoic eras were a time of gradual preparation for the birth of this Rocky Mountain front range. An erosional plain of low relief that had been developed upon the pre-Cambrian crystallines was flooded by the middle Cambrian sea. Repeated incursions in subsequent Paleozoic periods resulted in the deposition of a considerable body of sediments upon the site of the future range. The general region was upwarped somewhat during the closing stages of the Paleozoic era but was peneplaned before the transgression of the middle Jurassic sea.[1] Throughout the remainder of the Mesozoic era a huge mass of marine and continental sediments, with a large body of intercalated effusives, accumulated over the area. The ejection of the volcanics appears to have been a premonitory symptom of the orogenic revolution which was soon to involve this region. That not remote portions of the province were already being affected by notable uplift and erosion is attested by pebbles of Carboniferous limestones and presumably pre-Cambrian granite in the Fort Union formation near Cody, Wyoming.[2]

Early Teritiary orogeny.—The climacteric event in the growth of the Beartooth Range was the profound orogeny which resulted in the huge overturned anticline and the great overthrust fault along its northeastern flank. The precise date of this epochal deforma-

[1] D. D. Condit, "Relations of Late Paleozoic and Early Mesozoic Formations of Southwestern Montana and Adjacent Parts of Wyoming," *U.S. Geol. Survey*, Prof. Paper 120–F, 1918.

[2] D. F. Hewett, "The Shoshone River Section, Wyoming," *U.S. Geol. Survey Bull. 541*, 1914, pp. 105–6.

tion is unknown, but the combined evidence afforded by the Beartooth and Absaroka ranges clearly indicates that it took place long after the deposition of the Fort Union in the former, and long prior to the accumulation of the widespread "early basic breccias" in the latter.

The folding of the Fort Union formation during the first orogeny that affected the underlying Mesozoic strata has been previously pointed out in this paper. If the Beartooth overthrust was essentially contemporaneous with the Heart Mountain overthrust, and at present there is no reason to doubt this, it occurred not earlier than the middle Eocene and may not have taken place before the early Oligocene.[1] This conclusion by Hewett as to the age of the Heart Mountain fault is based upon these facts: (1) the overthrust beds in places rest upon the Bridger formation (middle Eocene), and (2) the "early basic breccias" (upper Miocene) "locally lie in channels cut 200 to 300 feet below the overthrust surface."[2] It is significant that the overthrust mass is tentatively estimated to have been about 15,000 feet thick near the mountain front. In view of the complete removal of this thickness prior to the ejection of the upper Miocene volcanics it is hardly probable that the faulting took place later than the Oligocene.

Epochs of Peneplanation.[3]—Prolonged erosion initiated by this uplift reduced the ancestral Beartooth Mountains to the surface of low relief that is partially preserved in the flattish summits along the crest of the present range. The conclusion that these summit tracts are remnants of an ancient peneplain rests not alone upon the fact of their accordant levels, but is substantiated by their flattishness over a considerable area of diverse rocks in the central part of the range.

The age of this summit peneplain can not be closely determined with certainty on the basis of the available evidence, but its limits can be fairly well established. Inasmuch as the Beartooth over-

[1] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, XXVIII (1920), 537.

[2] *Ibid.*, p. 555.

[3] For a more detailed discussion of this topic see a forthcoming article by the writer, "Rocky Mountain Peneplains Northeast of Yellowstone National Park."

thrust is post-middle Eocene, the peneplanation of the deformed mass most probably was not accomplished before the Oligocene, and perhaps not until the Miocene. Several lines of evidence, which are discussed in the forthcoming paper, point to the conclusion that this peneplain is not older than the Miocene, and may possibly be of Pliocene age.

After the completion of the summit peneplain the range was uplifted about 2,000 feet, with slight longitudinal warping and gentle tilting of the surface toward the southwest. This elevation seems to have resulted from renewed movement along the overthrust fault surface. The new cycle of erosion thus initiated continued until a large portion of the range was again reduced to an old age lowland—the present sub-summit plateau. The central part of the range remained above this extensive plain as unreduced remnants of the earlier erosion surface.

The age of this sub-summit peneplain can not be closely determined until the place of the summit peneplain in the erosional history of the range has been more accurately determined. It is evident, however, that this surface was produced in the erosion cycle which was begun by the deformation that elevated the earlier peneplain, and was closed by the uplift that resulted in the excavation of the present canyon-like valleys to depths of a few thousand feet. If the summit peneplain is as old as the middle Miocene it appears not improbable that the sub-summit peneplain is as young as the Pliocene, but if the former is of Pliocene age it is probable that the latter is of late Pliocene or early Quaternary age. Moreover, although the younger peneplain must considerably antedate the existing deep valleys, the fact that flattish remnants as large as 10 to 20 square miles in vulnerable positions have been but slightly dissected by tributary valleys strongly suggests that it may have been completed and elevated as recently as the Quarternary. The boldness of the mountain front, its abrupt rise for thousands of feet above the plains, and the slight amount of dissection over large areas support this view.

Quarternary events.—This second epoch of peneplanation was terminated by a vertical uplift of several thousand feet, which

enabled the streams to carve out the present system of sharp valleys. The movement was probably due to stresses that forced the overthrust mass still farther forward and upward along the fault surface. Warping of the uplifted peneplain appears to have been slight, as the difference in altitude may be due in part to the original slope of the plain. There is some suggestion in the stream profiles that the central part of the range was elevated more than the lateral or terminal portions. Westward tilting at this time is suggested by the fact that the valleys on the northeast side of the axial divide are cut much farther below the surface of the sub-summit plateau than are those on the southwest slope.

Another conspicuous result of the pronounced regional uplift has been the development of the bold plains-ward front of the range by differential erosion. The denudation of the highly resistant massive granite and gneiss has been comparatively slight since the uplift, whereas the much weaker Mesozoic and Tertiary (?) sedimentary formations of the adjoining plains have been worn to much lower levels.

Several subsequent broad elevatory movements of less vertical extent have successively rejuvenated the streams so that they have produced the series of terraces that exist along the principal valleys beyond the mountain front. The most recent important change of level seems to have preceded the earlier glacial epoch, for in East Rosebud Valley remnants of the right lateral moraine of this stage descend the streamward face of the first conspicuous terrace above the late glacial outwash.

The last noteworthy event in the history of the Beartooth Mountains was widespread glaciation during at least two distinct epochs. The glaciers on the northeast side of the summit divide were confined to the valleys whereas the plateau on the southwest slope was covered by the Beartooth ice-cap. Apparently the sub-summit plateau on the northeast slope has not been glaciated anywhere except at the heads of the valleys that rise within its borders, but it experienced considerable nivation. Meager remnants of the former extensive alpine glaciers still exist at the heads of several valleys on the northeast side of the main divide.

ACKNOWLEDGMENTS

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WAS THERE PENNSYLVANIAN-PERMIAN GLACIATION IN THE ARBUCKLE AND WICHITA MOUNTAINS OF OKLAHOMA?

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INTRODUCTION

At intervals since August, 1920, the writer has been investigating the problem of glaciation, in Pennsylvanian and Permian times, of the Arbuckle and the Wichita Mountains, and on several occasions since December, 1920, brief reports of progress, illustrated with various photographs and specimens of the supposed glacial evidence, have been presented to scientific societies.[1]

It was intended to continue the investigation during the present summer (1923) but the Governor's veto of the appropriation for the Oklahoma Geological Survey, which supplied funds for the field work, temporarily at least, postpones the completion of the researches proposed. The following paper, therefore, though somewhat more complete than any heretofore presented, is only a preliminary statement of the data bearing on the question of Pennsylvanian-Permian glaciation.

Although the data accumulated and described are wholly the work of the writer, it is important to refer to the earlier work of two other geologists, namely, J. A. Taff in 1905 and W. H. Twenhofel in 1917, who have suggested the probable glacial origin of certain deposits in regions outlying some distance from, but nevertheless of the same general Carboniferous age as, the features herewith described in the Arbuckle and Wichita Mountain areas. Their work will be referred to more fully later as they give a certain measure of support to the interpretations expressed in this paper.

[1] "Evidence of Glaciation in the Arbuckle Region," read before Geological Society of America, December, 1921; see Abstract, *Bull. G.S.A.*, Vol. XXXII, p. 91. Read before Am. Assoc. Petrol. Geol., March 17, 1921. Read before Oklahoma Academy Science, February, 1921; see Abstract, *Okla. Acad. Sci.* Vol. II. (1922), pp. 73.

THE BOULDER CONGLOMERATES

While the distinctive evidence of the supposed glaciation is furnished by the occurrence of polished, striated, grooved and deeply fluted rock surfaces, nevertheless these particular erosion features were discovered only as the direct result of investigating the origin of certain non-residuary boulder conglomerates which are widespread in the region. These conglomerates form a series of distinct beds ranging throughout a large part of the Pennsylvanian and well up into the base of the Permian. Although the striated rock surfaces are found in association with only some of the latest boulder conglomerates, these conglomerates are all essentially the same in character, hence it is inferred that they have had a common origin under glacial conditions.

The boulder conglomerates of Pennsylvanian-Permian age in the Arbuckle Mountain region that are believed to have been formed either directly or indirectly by glacial action, include what has been termed the Franks Conglomerate.

The Franks Conglomerate at the type locality in the vicinity of Franks (see map, Fig. 1), on the northeastern slope of the Arbuckle region, consists of several distinct beds of conglomerate each 100 to 350 feet in thickness, interstratified with limestone, shale, and sandstone. The lowest conglomerate bed is about 150 feet in thickness and overlies the eroded edges of the pre-Pennsylvanian rocks of the locality. The beds at higher horizons occur as intra-formational conglomerates within the Pennsylvanian. At least as many as five distinct conglomerate beds may be distinguished at Franks, and at other localities on the north side of the Arbuckles. The Franks, therefore, consisting of a series of conglomerates rather than a single bed, it is convenient to refer to it for the present at least as the Franks series. On the south side of the Arbuckle Mountains several beds of conglomerate like the Franks have been recognized in the Pennsylvanian series, though they are not so thick as those on the north side.

In the Wichita Mountain region there are also thick conglomerate beds essentially of the same type as the Franks series in the Arbuckles. But the Wichita Mountain conglomerates have not been called Franks Conglomerate, for they have been usually considered of later origin than the Franks.

The Arbuckle and the Wichita areas are the remnants of ancient mountain ranges that were elevated during Carboniferous time. Their uplift began soon after the Mississippian and apparently continued throughout a large part of the Pennsylvanian and into the early Permian.

It is obvious that in the general degradation of the Arbuckle and the Wichita Mountain areas the agents of erosion would first attack the youngest rocks of the uplifted areas and then in succession each of the older formations in the reverse order of their deposition. The Paleozoic sedimentaries, beginning with the Mississippian, were

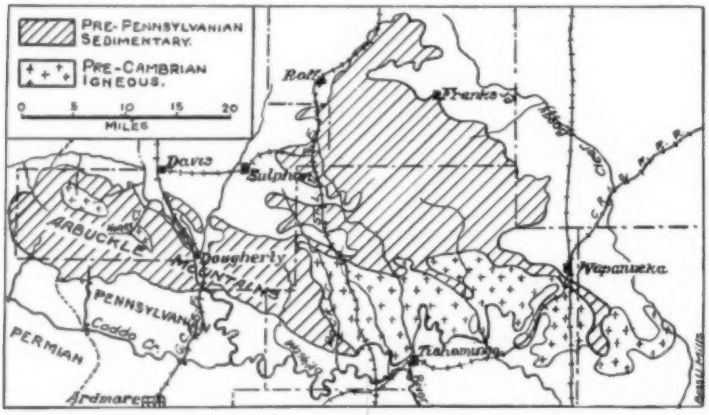

FIG. 1.—Sketch map of the Arbuckle Mountains

first removed before the underlying pre-Cambrian igneous rocks were exposed to erosion. In both areas, therefore, there are conglomerates of predominating Paleozoic limestone boulders formed in early Pennsylvanian times followed by conglomerates containing abundant pre-Cambrian igneous boulders of much later Pennsylvanian and Permian age.

In the Arbuckles, as now exposed, the conglomerates are largely of Paleozoic limestone boulders, and only some of the very latest conglomerates contain the boulders of the pre-Cambrian igneous rocks. On the other hand, in the Wichitas the pre-Cambrian igneous boulder conglomerates are the most abundant, and some of

the oldest of those now exposed as well as the youngest contain the pre-Cambrian boulders.

This difference in constituents of the conglomerates in the two areas is probably due to somewhat different conditions in the two areas which resulted in an earlier uncovering of the pre-Cambrian rocks in the Wichitas than in the Arbuckles. The earlier uncovering of the Wichita pre-Cambrian may have been due to a higher uplift of the Wichitas which resulted in faster erosion, or to a thinner covering of the Paleozoic, or to a combination of both of these conditions.

GLACIAL ORIGIN OF THE CONGLOMERATES

Whatever the correlation of these conglomerates it is their character and their probable origin to which attention is called. The glacial origin of the conglomerates is believed to be indicated by the following characteristics:

1. The heterogeneous character of the conglomerates, as indicated by the range in source of rock material and the great variation in size of the constituents in local deposits.

2. The non-residuary and unweathered character of the constituents of the conglomerate.

3. The great thickness of the conglomerate beds.

4. The occurrence of polished and striated surfaces of the rock floor upon which the conglomerate rests, and of polished, striated, and grooved pebbles and boulders in the conglomerate.

The phenomena described under the first three of these headings are of general occurrence and are everywhere exhibited by the conglomerate, while the features described under the fourth heading, which seem to indicate distinctive evidences of glaciation, are of more rare occurrence and are not everywhere developed or preserved.

In addition to the distinctive evidence of glacial origin furnished by the constituents of the conglomerate and the striated rock floors, there are on the flanks of the Arbuckle Mountains U-shaped valleys formed during the period of conglomerate deposition which possess the characteristic form of glacially eroded valleys. One of these U-shaped valleys, that of Honey Creek, has a polished and striated rock floor upon which the typical glacial conglomerate rests.

1. The heterogeneous character of the deposits is shown by a wide range in source, size and shape of the constituents of the conglomerate. Limestone is the most abundant boulder constituent in the Arbuckle area, as limestone is the most common rock of the Arbuckle region. In general, limestone pebbles from all the Arbuckle Mountain formations older than the particular conglomerates are brought together in each of the local deposits. In places there may be a predominance of boulders from adjacent or underlying formations, but very generally there is a complete mixture in varying proportions of rock débris derived from a wide range of formations. While there is a general tendency for coarse and fine beds of conglomerate to succeed one another, the individual beds show very little or no assortment. In the same bed the constituents will usually range from small pebbles up to boulders from 1 to 3 feet in diameter.

The shape of the pebbles and boulders also varies greatly, ranging from rounded to sub-angular and angular. In some deposits angular constituents predominate, in others rounded boulders are most abundant. Usually the more rounded and polished the boulders the greater the distance they have been transported. In some of the beds, at least, the most angular blocks have been derived from adjacent formations. However, any generalization meets with many exceptions, and well-rounded and very angular material from the various formations are often found together.

2. The non-residuary character of the pebbles and boulders is one of the most striking characteristics of the conglomerate. The constituents do not represent the end products of weathering, such as generally characterize basal conglomerates formed under ordinary sub-aerial or sub-aqueous conditions. On the other hand, the constituents are easily decomposable carbonate and silicate rocks which, judging from their angular shape and fresh, unweathered character, have been removed rather rapidly from their original source and transported considerable distances without much chemical decomposition.

It is well known that conglomerates or breccias formed of non-residuary material are characteristic of deposits on mountain slopes accumulated under desert conditions. The character of these

Pennsylvanian conglomerates, however, is such as to indicate their fairly constant association with water, as shown by the presence of many rounded water-worn pebbles and boulders, and their deposition in fairly distinct coarsely stratified beds. Furthermore, the Pennsylvanian conglomerates are not associated with any deposits suggestive of arid or desert conditions, such as the salt and gypsum deposits formed in later Permian time, but are on the other hand associated with coal seams and dark-colored carbonaceous shales indicating a relatively humid climate such as is required for abundant vegetation.

3. The great thickness of single conglomerate beds repeated at intervals in a series, is another striking feature. In the section at Franks there are at least five distinct conglomerate beds or formations, each ranging in thickness from 150 to 350 feet. In the section along Honey Creek, near Davis, the conglomerate is between 200 and 300 feet thick. There are other places where the thickness may reach as much as 1,000 feet or more. Such great thicknesses of conglomerate, it is believed, are rarely if ever formed upon the shores of ancient or present seas under ordinary conditions. On the other hand, such thicknesses of raw, unweathered débris are the common characteristics of conglomerates formed upon land, or in adjacent sea bottoms where glacial conditions exist, or have prevailed in the past.

4. In addition to the above-described characteristics which are usual features of glacial formations, there are the phenomena of striation and grooving which are believed to furnish the distinctive evidence of glacial action.

It may be thought by some that the striæ about to be described and illustrated by these specimens may have been formed by some other means than glaciation, such as by artificial means, or by such rock pressure movements as are developed along joint planes and fissures, in the manner of slickensided surfaces. There are, of course, various kinds of marks to be observed on rocks, both artificial and natural, and it seems hardly necessary to state that these various phenomena have been considered in the search for evidence of the glacial origin of these conglomerates. There are, for instance, numerous examples of polished and grooved surfaces developed

along joints and fissures in the closely folded and faulted pre-Pennsylvanian rocks of the Arbuckle region. Detached from their position along fissures some slickensided specimens might be taken for specimens showing glacial striæ, but no one observing such phenomena should have any difficulty in distinguishing glaciated surfaces from purely rock pressure surfaces in field exposures, because they are formed under quite different geological conditions, and are invariably to be observed under entirely different geological environments.

It should be stated in this connection that the most abundant striations and other evidences of supposed glaciation appear to be associated with one of the latest, if not the latest, conglomerate, deposited in both the Arbuckle and Wichita regions. This is especially true of the striations on the rock floor on which the latest conglomerate rests. However, some striated boulders and pebbles within the conglomerates have also been discovered in much earlier beds.

STRIATED ROCKS IN THE ARBUCKLE MOUNTAINS

The striæ thus far observed on the rock surfaces beneath the conglomerate in the Arbuckle region range from fine lines to fairly prominent grooves reaching an inch in width and one-fourth inch in depth. They usually run in nearly parallel directions and form distinct markings varying from a few inches to several feet in length.

The striated rock surface, shown in Figure 2 was found along the Santa Fé Railroad about $2\frac{1}{2}$ miles north of Daugherty, where the underlying floor is exposed beneath a small projecting mass of the conglomerate. After two attempts by the writer to take a satisfactory photograph of this example in the field had failed, a fragment of the striated floor, (Fig. 2) was removed and photographed in a studio at Norman. The striæ at this place have a trend N. 25° E., as indicated by their position combined with the fact that the conglomerate overlying the striated floor contains abundant porphyry boulders and cobbles derived from porphyry outcrops (East Timbered Hill) which occur to the west. One of these porphyry cobbles which exhibits distinct grooving, and finer striations

FIG. 2.—Striated fragment of rock floor, 2½ miles north of Dougherty

on the large groove, is shown in Figure 3. Other examples of striated boulders were found in the same locality.

Very fine striations are developed on the limestone floor of the conglomerate in the valley of Honey Creek about a mile below Turner Falls (see Fig. 4). The finely striated floor of the conglomerate is in the flat bottom of a distinctly U-shaped valley with relatively steep walls rising about 200 feet high. The smooth undulating rock floor covered with a few small patches of conglomerate is shown in Figure 5.

FIG. 3.—Grooved porphyry cobble in conglomerate overlying striated floor of Fig. 2.

The history of Honey Creek Valley and others like it on the flanks of the Arbuckle Mountains is complex, and deserves a special article in itself. The valley is U-shaped, especially below Turner Falls. It is mainly carved out of rocks of pre-Pennsylvanian age but in part also out of coarse boulder conglomerates of early or middle Pennsylvanian age, all of which have been folded to a variable degree and faulted. In the bottom of the U-shaped valley there is a formation of much later horizontally bedded conglomerate, made up of boulders of various sizes up to over a foot in diameter, which lies directly across the faults that affect the rocks of the valley walls. This undisturbed conglomerate, made up of boulders many of which are porphyry derived from points at least a mile or more away, can be traced out and grades into beds of finer sediments that surround the mountains and are considered to be at the top of the Pennsylvanian or in the basal portion of the Permian.

The smooth and striated floor of the valley lies beneath the horizontal conglomerate, and is exposed only where the present stream bed of Honey Creek happens to coincide with the old valley floor. The present stream develops a rough and jagged rock bed with-

out smooth and striated surfaces and it rapidly destroys and obliterates the smooth surface after removing the conglomerate. The striated surface is therefore found only beneath the conglomerate,

FIG. 4.—Striated fragment of floor of Conglomerate, Honey Creek valley

or where the conglomerate has been removed recently by the erosion of the present stream. Obviously the striated floor was formed under a set of erosion conditions quite unlike those now occurring in the valley. While the striations of the floor of the conglomerate are very fine (see Fig. 4), perhaps too fine to be especially distinctive

of a glacial origin, their occurrence in the bottom of a U-shaped valley and in direct contact with boulder conglomerates, both of which features are usually associated with glaciation, furnish a combination of geologic evidence strongly supporting the evidence of their glacial origin.

A striated limestone surface occurs along a branch of the Frisco Railroad about five miles east of Sulphur, where it was exposed by the removal of one to two feet of surface formation in constructing the railroad grade several years ago. This locality shows fairly

FIG. 5.—Polished smooth floor of Conglomerate, Honey Creek valley

prominent striæ and grooves, the more prominent of which are about three-fourths inch in width and about one-fourth inch in depth, some of them having a continuous length of about two feet over the smooth undulating limestone surface. The exposure is a gently sloping land surface of an upland area rather than a valley bottom.

The striated surface consists of the Arbuckle limestone, and is the floor of a late Pennsylvanian conglomerate that lies in patches in the vicinity, forming a continuous thick body a short distance to the west but thinning out to the east. The grooves have a trend nearly E.–W. and all are approximately parallel to one another.

There are some fresh irregular marks on the rocks apparently made by blunt iron tools during the process of excavating for the railroad grade, but these are quite unlike the grooves thought to be of glacial origin. The grooves thought to be of glacial origin are all essentially parallel in position, and many of the larger grooves show fine scratches superposed upon the grooves as though made by stony material having projecting sand grains.

FIG. 6.—Striated fragment, 5 miles east of Sulphur

No good photograph of the striated surfaces is available but in a recent visit to the place, there was found in the surface formation that overlies it, the fragment of limestone shown in Figure 6. This loose fragment is striated and grooved on two opposite sides and is apparently only a small portion of a larger flat piece of limestone that was subjected to abrasion when the overlying conglomerate formation was deposited.

GROOVED AND FLUTED GRANITES OF THE WICHITA MOUNTAINS

In the western part of the Wichita Mountains (see map, Fig. 7) there occur on the lower slopes of the mountains, numerous examples of polished, grooved, and fluted granite surfaces that have a marked resemblance to the work of ice erosion. Up to the present time the best examples have been seen southwest of Hobart, but not unlikely they may later be found to occur to some extent over the entire region. These grooved granites have been observed by other geologists who have visited the region, but they appear to have been referred to in the literature only by C. H. Taylor[1] who mentions

[1] "Granites of Oklahoma," *Okla. Geol. Survey, Bull. 20*, Plate XI, 1915.

the grooving incidentally in connection with a detailed description of the granites. It should be stated also, that the present writer has not yet seen all the examples of grooved granites reported to occur in the area.

The granite shown in the following illustrations is medium to coarse grained, of uniform granite texture, without any lines of

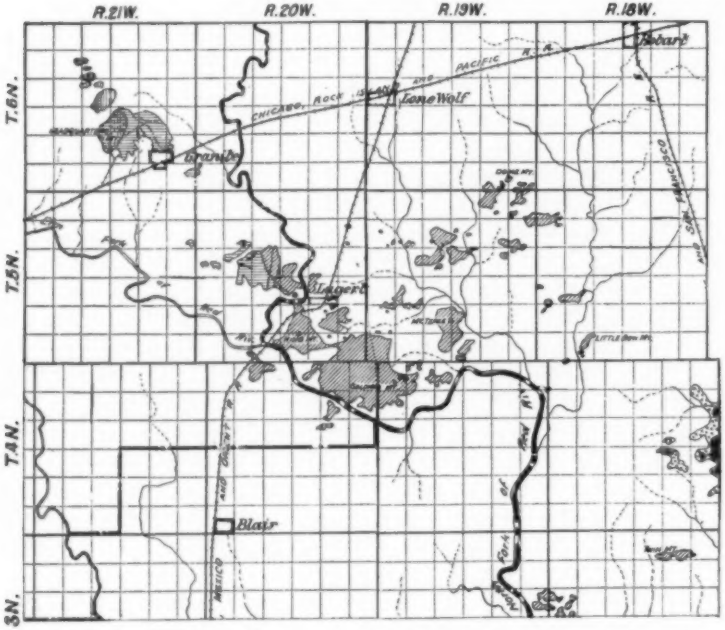

FIG. 7.—Sketch map of western part of Wichita Mountains. Shaded areas represent granite mountains, unshaded the plains of the Permian Red Beds.

structure or banding developed in it, excepting the numerous irregular joints and joint cracks that extend throughout. The grooves and flutings, therefore, depend in no way upon structural features of the granite formation.

The distribution of the grooved granites is limited to the lower slopes of the mountains about 100 feet above the lowest lands immediately adjacent. In their occurrence they are in close proximity

to coarse boulder deposits that occupy the lower slopes of the mountains. The boulder conglomerates are much eroded by the present surface drainage, and on the lower slopes they appear as remnants of a more continuous formation that once filled the intermontane valleys.

Above the general level of the zone of the grooved granites and the boulder conglomerates, the granite walls of the mountains rise to heights of 200 to 800 feet from the surrounding plains of the Permian Red Beds, and on these higher slopes are developed (see Fig. 16) the characteristic jagged or rounded exfoliation features, developed by granite under the stress of wind and weather.

FIG. 8.—View of grooved granite

The character of some of the grooved granite surfaces is shown in Figures 8, 9, and 10, which are examples occurring near the base of a granite mound that rises about 200 or 300 feet above the Permian Red Beds plain in the N.E. part of Sec. 7, T. 5 N., R. 18 W.

Figure 8 shows deeply grooved granite near the base of the mound with the border of the plain sloping down to the right and with the top of the mound rising up on the left. The grooves are seen to extend around the outcurving heads of the projections and, though they disappear beneath the talus in the re-entrants in this particular place, they are believed to continue across as is indicated in Figure 11. The system of nearly, but not exactly, parallel grooves is approximately horizontal in this example. The grooved surface is roughened by spalling and other weathering processes, and the

middle projecting head has slumped appreciably from its original position.

A close view of another example of the grooved surface is fairly well illustrated in Figure 9, which shows grooves over one foot across and one-half foot deep. The ridges between the grooves show spalling and roughening by weathering. The sharpness of the grooves cut into the massive granite is illustrated in Figure 10, which shows a large block slumped down from the grooved zone adjacent. The grooved surface of Figure 10, because of its protected position on the under side of the turned-over-block, remains smoothly polished while the grooves shown in Figures 8 and 9, where unprotected and exposed to the sun, rain, and wind, are very rough.

FIG. 9.—View of grooved granite

The grooved granite surfaces are preserved to a variable extent on all sides of the mound, but the best examples, those shown in Figures 8, 9, and 10, are on the south side. In the re-entrant between two of the outcurving heads, partly covered by loose débris, a boulder was found fitting closely into one of the grooves. The side of the boulder next to the grooved surface was shaped to fit the groove as though it had been shoved along the groove by some semi-rigid body, such as ice, moving along the mountain side.

The continuity of the grooves and striæ about the outcurving heads and back into the re-entrants seems fairly well indicated in Figure 11. The grooved wall shown has a height of about 20 feet and as many as 50 or 60 distinct grooves and striæ are observable

on the largest face. While actual continuity of the striæ is broken in the farthest recess of the re-entrant where surface waters, after heavy rains from the slopes above, have concentrated and worn them away, there seems little reasonable doubt of their original continuity. The surface of the granite has been roughened by

FIG. 10.—View of grooved granite, overturned block

FIG. 11.—View of grooved and striated granite

present weathering processes, but examples a short distance to the north show grooves with smooth and polished surfaces.

The manner in which the grooves and striæ entirely encircle small isolated stacks and bastions of granite is shown in Figures 12 and 13, which are views of the same rock taken from opposite sides. Although this particular example has been incidentally referred to

by Taylor[1] as a grooved boulder, it is the writer's interpretation that it is the top of a granite stack whose base is buried beneath the valley deposit. This interpretation finds visible support at least in the observations that no distinctly loose boulders of this type were seen in the area, and such grooved surfaces as these are known to entirely encircle some of the granite hills.

The grooved granite stands at the lower end of a valley on the south side of King Mountain, about two miles south of Lugert. The valley opens out to the south into the North Branch of the Red River. Figure 12 is a view of the granite stack with the east side

FIG. 12.—View showing grooves encircling granite stack. Seen from east side.

FIG. 13.—View showing grooves encircling granite stack, same as Fig. 12. Seen from west side.

of the mountain nearby in the background. On the left, at the same level as the grooved granite stack, the valley side shows some grooved surfaces, and on the slope higher up is a notch cut into the side of the mountain indicating what may be some faint traces of an ancient terrace. The opposite or west side of the grooved granite with the central part of the valley in the background is shown in Figure 13.

The grooved granite stack is elongated in a direction parallel with the valley, and its north end facing up the valley (to the right in Figure 12 and to the left in Figure 13) has a distinctly steeper and more abrupt face than its south end which faces down the valley. The end facing up the valley has the appearance of being undercut by the force of erosion that developed the encircling grooves, and

[1] C. H. Taylor, *Okla. Geol. Survey, Bull. 20,* Plate XI, p. 61.

this force was obviously directed by an agency which moved down the valley.

It may be assumed for the present that if glaciation was the cause of the extensive deposition of conglomerates, and of the various striated and grooved rocks just described, it was a type of valley glaciation developed on mountainous areas which probably stood as islands in the Pennsylvanian-Permian seas. There is no evidence from the conglomerates themselves to indicate anything other than their local origin, either within the Arbuckle Mountain area, or within the Wichita Mountain area. Perhaps in some places within the area between these mountains, there may have been a commingling of materials derived from the two mountain sources, but these places are now deeply buried by the later Pennsylvanian and Permian sediments. The present data therefore indicate that the glacial source was in the mountains adjacent to where the boulder conglomerates and the striated and grooved rocks are found.

Under this hypothesis the glaciers having their sources in the mountains descended the valleys and coalesced on the low lands, or in the seas that surrounded the mountainous islands. The present valleys occupy the lines of ancient drainage, and ancient valley glaciers, in moving down the valleys, would be in a position to develop such features as the grooved granite of Figures 12 and 13, which closely resemble the features of "crag and tail" of glacial origin. In the phenomena of "crag and tail"[1] isolated stacks and bastions of rock which faced the direction of ice flow are rounded and beveled off and frequently a hollow is dug out in front, while débris has been heaped up behind to form the so-called "tail" of the hill.

In the valley which contains the grooved granite stack are coarse boulder deposits in contact with the grooved granites which indicate some adequate means for the transportation of coarse débris from farther up the valley. In Devil's Canyon Valley, which lies adjacent to the east, there are grooved granite walls at various places along the valley which appear to indicate a marked descent of the grooves down the valley. While there is some rather steeply inclined grooving of the granite in this region (see Fig. 14), the grooves and flutings are in general approximately horizontal. Furthermore

[1] J. Geikie, *Earth Sculpture*, p. 242.

some of the valleys that lie on the flanks of the Wichita Mountains like that of Honey Creek in the Arbuckle Mountains, appear to have the distinctly U-shaped form which is typical of glaciated valleys. A probable example of a U-shaped valley in the eastern part of the Wichita Mountains appears to be that of the gorge of Canyon Creek, in Sec. 2, T. 4 N., R. 13 W.

The suggestion has been made that the grooved granites owe their origin to wave action of some sort. Indeed, in so far as explanations of these features have been offered, some form of water wave work has usually been suggested. The writer, however, can find no reference in literature to features of this sort made by water waves.

FIG. 14.—View showing inclined grooving

On the other hand the grooved and fluted granites bear a marked resemblance to the work of ice erosion, such as the rock scorings of various kinds described by T. C. Chamberlin[1] from the Pleistocene glaciation.

If the grooved granites are relics of ancient glaciation, the question naturally arises as to what has protected them from Permo-Carboniferous times to the present. As already stated the fluted surfaces appear only on the lower slopes of the mountains in a zone now occupied by the remnants of a coarse boulder conglomerate of Permo-Carboniferous age that once filled the intermontane valleys. The grooved granites are seen only where recent removal of the conglomerate by stream erosion has exposed them to view.

[1] T. C. Chamberlin, "Rock Scorings of the Great Ice Invasions," *U.S. Geol. Survey, 7th Annual Report*, 1886, pp. 155–248.

In Figure 15 is shown an example of recent uncovering of a fluted granite mass. This view shows in the foreground a small area of fluted granite standing on a low flat which has been exposed by stream erosion. In the background is seen a bank rising above the flat, which is the general level of the surrounding plain of the Permian Red Beds. The Red Beds once extended over the intervening low flat and completely covered the granite mass, but stream erosion has recently removed the Red Beds down to the intervening low flat, thus bringing to view the buried granite with its fluted surfaces. In addition to the work of streams ordinary slope

FIG. 15.—View showing recent uncovering of grooved granite

wash on the sides of the mountains, has exposed the grooved surfaces as in such examples as Figures 8 and 11.

An additional line of evidence in support of the view that the fluted granite surfaces are ancient features, brought to the surface by the removal of the valley fill, is the very obvious fact that these features are now in process of obliteration and destruction wherever exposed to present weathering conditions.

The present type of wind and weather action is fairly well illustrated in Figure 16, which represents an exposure at the head of Devil's Canyon and well above the zone of valley fill and grooved granite surfaces. This granite mass is an isolated stack, exposed

to the rigid action of wind and weather, resulting, as usual under such conditions, in the opening up of deep cracks along the penetrating joints and the weathering out of large blocks which become more or less rounded by exfoliation. There is no indication in this example, or anywhere else in the region, that the present type of weathering tends to produce the fluted granite surfaces. On the other hand the present type of weathering tends to destroy the grooved surfaces. Figures 8, 9, 10, and 11 show the fluted granites in various stages of destruction. Note how the surfaces of the flutings are roughened and the projecting ridges between the grooves

FIG. 16.—View showing features of the granite under present conditions of wind and weather.

broken off by spalling. Some of the outcurving heads are in process of slumping down the mountain slope and some lie completely dislodged and turned over.

Originally the fluted surfaces were smooth and highly polished as shown by the fact that in the most protected places the flutings are still smooth and polished. Some of the fluted granites are so markedly polished that they have served as favorable places for the pre-Kiowan Indians to carve their picture writings, obviously for the same reason that our granite workers select only the polished surface of monuments upon which to trace their finest lines of engraving.

The boulder conglomerates associated with the granite mountains in the western part of the Wichitas are largely granite material without appreciable amounts of calcareous cementing constituents and hence in most places are an unconsolidated formation. But where limestone material is abundant in the conglomerate, it is usually a firm consolidated formation. The unconsolidated character of much of the conglomerate composed of igneous rock boulders, sand, and clay has led to the suggestion that it may be of a later age than the Permian Red Beds. However, there seems no good reason to doubt the usually accepted correlation stated by Taff[1] that the boulder conglomerates at the base of the mountains are of the same age as the red shales and sandstones into which they appear to grade in the surrounding "Red Beds" plains.

WORK OF OTHERS

While the data bearing on the problem of Pennsylvanian-Permian glaciation here presented are wholly the work of the writer, it is important to refer to the earlier work of two other geologists who have either ascribed directly or at least suggested the possible glacial origin of certain Permo-Carboniferous deposits within the general region, but outlying some distance from the Arbuckle and Wichita mountain areas.

J. A. Taff, in 1905[2] and in 1909,[3] described the occurrence of erratic boulders in shales of Middle Carboniferous age in the Ouachita Mountains of eastern Oklahoma. The erratic boulders consist of various types of rock such as limestone, sandstone and quartzite, some of which are angular and ranging in size up to 50 feet in diameter. It was Taff's belief that the erratic boulders were ice-borne and derived either from the Arbuckle uplift or from associated areas farther to the south in Texas.

Taff seems not to have discovered any distinctive evidence of glacial striæ on the boulders described by him, and in 1912, J. B. Woodworth,[4] after making some investigations, reached the con-

[1] J. A. Taff, *U.S. Geol. Survey*, Professional Paper 31, p. 76.

[2] *Science*, Vol. II (1905), p. 225.

[3] *Bull. Geol. Soc. Am.*, Vol. XX (1909), p. 701; and *Science*, Vol. XXIX (1909), p. 637.

[4] J. B. Woodworth, *Bull. Geol. Soc. Am.*, Vol. XXIII (1912), pp. 457–62.

clusion that certain chert boulders mentioned by Taff in folded Carboniferous shales near Talihina, Oklahoma, had been shaped by earth movements and not by glacial action. The writer has seen these chert fragments in the folded and faulted shale at Talihina where they reveal abundant evidence of earth movements and agrees fully with Woodward's interpretation of their origin. It should also be stated that Taff fully recognized that certain marks on boulders described by him resembled slickensided surfaces.

There are, nevertheless, certain formations of Carboniferous age in the Ouachita Mountains of eastern Oklahoma containing a mixture of various kinds of large boulders derived from different sources, the origin of which as stated by Taff is difficult to explain, except in some manner through the agency of ice, probably the work of icebergs. If the evidence presented by the writer in the Arbuckle and the Wichita mountain areas indicates Carboniferous glaciation, the erratic boulders described by Taff would seem to fall naturally into the same category.

W. H. Twenhofel[1] in 1917 in a paper entitled "Granite Boulders (?) in the Pennsylvanian Strata of Kansas," described numerous large boulders, mainly of granite porphyry within the area occupied by formations of Pennsylvanian age near Rose, Woodson County, Kansas. Many of the boulders are as much as four feet in diameter, the largest being seven feet in diameter, and they appear to be unlike the granite boulders of the Pleistocene drift, the southern limit of which lies about 75 miles to the north. The boulders are now exposed on Pennsylvanian strata and while their correlation could not be fully determined, Twenhofel is inclined, for various reasons, to consider that they are of Pennsylvanian rather than of Tertiary or Pleistocene age, and that the boulders reached their present position through the agency of ice, either glacial or floating, more probably the latter. The possibility that the Rose boulders may be correlated with the Squantum tillite near Boston, Massachusetts, described by Sayles[2] is suggested by Twenhofel.

There are, therefore, in the rocks of Carboniferous age, some distance from but within the general region of the Arbuckle and the

[1] *Am. Jour. of Science*, Vol. XLIII (1917), pp. 363–80.

[2] *Bull. Mus. Comp. Zoöl.*, Vol. LVI, No. 2, Geol. Series, Vol. X (1914), pp. 141–75.

Wichita Mountains, as well as in more distant localities, as Massachusetts, certain deposits, the origin of which is much more reasonably ascribed to glaciation than to any other agency. It is, of course, now generally accepted by geologists that extensive glacial deposits were formed on all of the continents, except North America, during Carboniferous times. This fact, however, should not be given undue weight in support of the view that particular glacial-like deposits are necessarily of glacial origin because they were formed in the Permo-Carboniferous times. The character of the deposits and associated features themselves should furnish reasonable evidence of their glacial origin, if such is their origin.

However, marked changes in climate are known to be world wide in their effects and it would seem highly probable that if Permo-Carboniferous glaciation did so powerfully affect the other continents, such as Asia,[1] Australia,[2] Africa,[3] and South America[4] in particular, it should almost certainly have affected North America over considerable areas. If this were the case, such regions as the Arbuckle Mountains and the Wichita Mountains, which stood as high land areas during this period of general glaciation, would have been so situated that glaciation might reasonably be expected to have developed there.

[1] For an account of Paleozoic glacial phenomena, see C. D. White, "Carboniferous Glaciation in the Southern and Eastern Hemispheres," *Am. Geol.*, Vol. XIII (1889), pp. 299–332.

[2] W. E. David, *Q.J.G.S.*, Vol. LII (1896), pp. 289–301.

[3] Broom, *Geology of Cape Colony.*

[4] I. C. White, *Geol. Soc. Am.*, Vol. IX, pp. 512–21.

SOME EXPERIMENTS IN FOLDING

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University of Chicago

In 1812 Sir James Hall, using some pieces of cloth and a door "which happened to be off its hinges" and a few stones to act as weights, reproduced the contortions of the strata shown by the Berwickshire coast. This suggestion was revolutionary, for folding of strata had not previously been recognized.[1] Since that beginning, experimentation in folding has been carried on by many different investigators, among whom may be mentioned Favre, Daubrée, Pfaff, Forscheimer, Schardt, Reade, Cadell, Willis, Avebury, Paulcke, Königsberger, and Mead. No attempt will be made here to discuss in detail the results of these researches.

For many of the present experiments the pressure apparatus utilized was the crushing box previously used for experiments in faulting which have already been described.[2] Pressure can be applied simultaneously from both ends, if desired. As one side of the box can be removed at will, the progress of the folding can be observed and photographed at any stage of the deformative process. A comparison of the progressive changes and characteristics of the folds during the different stages of compression constituted an important part of the investigation. In most of the tests sand was placed both above and below the layers to be folded. This gave an adaptive support below, and effected a well-distributed weighting above. Heavy blocks of stone were placed upon the sand to afford sufficient overburden.

After testing various materials, mixtures of paraffin and vaseline were found to yield the most satisfactory results, and were employed in different proportions, depending upon the degree of competency desired. Pure paraffin was found to be too brittle for pronounced

[1] J. S. Flett, "Pres. Address, Sec. C," *Rept. British Assoc. Adv. Sci.*, 1921, p. 73.

[2] R. T. Chamberlin and W. Z. Miller, "Low Angle Faulting," *Jour. of Geol.*, Vol. XXVI (1918), p. 11.

folding, and is far better adapted to experiments on faulting. On the other hand, a layer of pure vaseline between stronger layers is extremely incompetent. The competency of experimental materials can thus readily be regulated by varying the relative proportions of the softening and hardening constituents. In some cases a small amount of plaster of Paris was added to develop the most competent layers. In preparing the succession of strata each layer was molded separately in a wooden frame having a paper bottom. With the materials used the layers were sufficiently plastic to weld together in a firm block of strata which was then placed in the compression box.

Criticism has sometimes been leveled at compression-box experiments, but the opinion may perhaps be ventured that observation of the stages of deformation of three-dimensional blocks gives one a much clearer conception of the processes of folding than can be obtained by a study of field sections. In addition there were many interesting and unexpected developments which arose independently of the main purpose of the investigation.

Mead has suggested that pressure-box experiments do not make accurate reproductions of folding as it occurs in nature, because they do not take into account the shrinkage of the earth beneath the mountain zone.[1] In Mead's very neat and effective experiments a tightened rubber band with a paraffin coating was allowed to shrink and thus deform the paraffin. This method would seem to rest on the assumption that the sub-crustal portion beneath the mountain range is shortening by compacting as much as is the mountain range by folding, but one may perhaps urge the alternative hypothesis that the shortening by compacting of the sub-crustal zone is more widely distributed under plain and mountain range, while in the crustal portion the shortening tends to be concentrated in the mountain ranges. On this hypothesis the compressive movements which produce the folding are not only the product of the compacting beneath the ranges, but also to a greater degree the product of the accumulated movement of the non-mountainous parts of the crust toward the growing mountains. The very common location of mountain ranges parallel or concentric with conti-

[1] Warren J. Mead, "Notes on the Mechanics of Geologic Structures," *Jour. of Geol.*, Vol. XXVIII (1920), p. 507.

nental borders and coast lines, seems to be an expression of directed horizontal thrusts which are only in part the result of earth shrinkage immediately beneath the mountains. Thus the pressure-box method, with its tangential forces, though not taking into account forces developed by compacting directly beneath the deformed strip, still possesses some advantageous features not possessed by the shrinking rubber-band method.

The present paper will discuss the bearing of some of the experimental results on geological theories.

ARCUATE TREND LINES

The remarkable arcuate chains of Asia and southern Europe have given rise to considerable geologic speculation. Suess assumed that in the case of Asia these arcs were produced by thrusting directed from the interior of the continent outward and toward the concave sides of the arcs.[1] In harmony with this, is the most commonly held view that, in general, the thrusting which has produced arcuate ranges has been directed against the inner or concave sides of the curves.[2] Hobbs, on the other hand, believes that in the formation of arcuate mountains, the active thrusting has been directed against the outer or convex side.[3] This belief was derived in the first place from theoretical considerations substantiated in his opinion by an experiment. In this experiment compressive stress was applied on two sides of what was essentially an equilateral triangle while the apparatus itself offered resistance on the third side.[4] The resulting folds naturally tended to form approximately normal to the compression which, in this case, produced an arc whose outer side faced the compression—the result sought. But one may readily suspect that if the thrusting could be made to act in just the opposite direction—from within the triangle outward against the steel sides

[1] Eduard Suess, *The Face of the Earth*, Sollas Trans., Vol. I, Part II.

[2] H. A. Brouwer, "On the Crustal Movements in the Region of the Curving Rows of Islands in the Eastern Part of the East Indian Archipelago," *Konig. Akad. Wetenschappen Amsterdam*, Vol. XXII (1916), Fig. 1, p. 775. O. Wilckens, *Allgemeine Gebirgskunde* (Jena, 1919), pp. 49–60.

[3] W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 71–90; 166–88; 193–208.

[4] *Ibid.*, Fig. 8, p. 89.

of the frame—it would produce wrinkles with essentially the same trends. The above experiment did not appear to the present writers to decide the question. It seemed desirable to try experiments of a somewhat different sort.

Experimental results.—A rectangular model of much greater area than is possible in the pressure box was placed in position with side supports and an appropriate overburden. It was arranged so that pressure could be applied over a limited portion of the free side, either by a single steel jackscrew, or by two jacks operating inde-

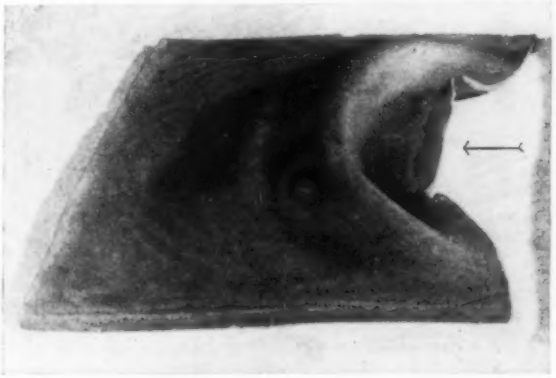


FIG. 1.—Arcuate fold produced by jack-screw in the position shown by arrow. The inner side of the arc faces the thrust.

pendently on different portions of the free side. By applying pressure over only a short strip of the model very good arcs were developed. The lines of force apparently radiate outward from the locus of active thrusting. The wrinkles then form more or less normal to the lines of greatest compression, developing curves whose concave sides face the thrusting. Thus it is found that arcs can be developed readily enough from compressive stress directed outward from a place within the inner curve of the ensuing arc (Fig. 1).

In the formation of many mountain ranges the intensity of thrusting has presumably varied from place to place, as suggested by the fact that the ranges are not entirely continuous. Places of greatest thrusting and greatest horizontal shifting of material would

present some analogies to the loci of applied thrust in the experiments just described. In such places arcs might develop with their inner curves toward the active force (Fig. 2). As a general rule, it is probably also true that the effects of the thrusting have presumably been somewhat greater in the middle portion of each range and have died off toward the extremities. Short mountain chains, in which the horizontal movement is considerable in proportion to the length, might perhaps develop curving trend lines because of this fact.

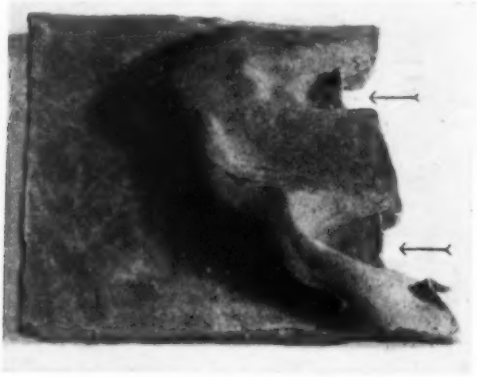


FIG. 2.—Force applied by two jacks (arrows) produced these arcuate folds. Their concave sides face the loci of applied thrust.

To test another possibility, a model was prepared in which a semicircular rigid plaster mass was incorporated in the usual relatively plastic mixture of paraffin and vaseline as shown in Figure 3. This would represent a rounded central mass of resistant old rocks, flanked by a zone of less consolidated sediments, after the analogy of Asia. The resistant plaster arc was placed on the side of the model farthest from the pressure which was applied uniformly by means of two steel jacks. It was suspected that the curvature of the resisting buffer might control, or at least greatly influence, the trend of the resulting fold. The result of the experiment was that while the fold manifested a slight tendency to conform to the curving outline of the resisting mass where the fold came closest to it, still the

tendency was not very marked. In general the trend of the fold did not conform to the shape of the rigid arc.

This would suggest that the curving mountain chains flanking the more rigid Tibetan mass do not, in the main, owe their concentric trend directly to the outline of the resisting mass. More likely in most cases it would seem that the belts of heavy sedimentation in geosynclinal tracts bordering the periphery of an elevated land mass, which also should have a slight curvature, may be the real factors which have determined the curving chains subsequently developed. A more or less circular or rounded land mass should naturally yield heavy sedimentation along its borders. Because of the relative weakness of these zones of sediments, and because of other factors

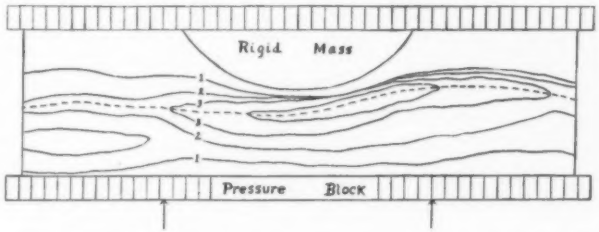


FIG. 3.—Result of deforming model between pressure board and rigid plaster mass. Folds contoured. Dash line indicates crest of principal anticline.

which cannot be discussed here, folding into mountain ranges subsequently appears in these marginal belts. Then, in the long geologic history the destruction of one range furnishes the material close at hand in more or less concentric belts, for the elevation of the next chain in some subsequent orogenic outburst. These successive generations of mountain chains follow a sort of cycle. The details of trend in a given range thus may be foreshadowed in part long in advance, and constitute an inheritance from a long sequence of ancestral conditions.

The problem of arcuate folding was studied from another angle. Inflated toy balloons were coated with paraffin by immersion in the hot liquid. After the paraffin had cooled somewhat, but was still quite plastic, the air in the balloon was allowed to escape slowly, causing the surface of the balloon to shrink. The paraffin, con-

forming to this shrinking surface, necessarily was folded or faulted. In many cases the axes of these folds were curved; in some places they formed arcs as intricate as the mountain ranges in the East Indies and southeast Asia. They suggest that arcuate folding may be the characteristic way in which a globe is deformed by internal shrinkage.

It would seem probable, therefore, from these various experiments, that mountain arcs are produced in several ways. A natural tendency of a globe undergoing deformation to yield along curved rather than straight lines is apparently a basal factor in the development of such ranges. This factor would operate, either by producing curving geosynclines through a long chain of ancestral conditions, or in some cases more immediately by developing curving folds directly. Such arcs would have their curvature already outlined in the early stages of the deformation. In addition, if the active force is from one side, or more from one side than the other, a progressive bending of the trend lines may occur as folding progresses, due to the holding back of the extremities while, with the maximum thrust in the center, that portion moves forward in a horizontal shearing movement, forming an arc which is concave toward the active pressure.

OVERFOLDS AND UNDERFOLDS

In Suess' explanation of the arcuate mountain zones of Asia and the festooned islands off the Asiatic coast, the active thrusting was supposed to come from the inner side of the arcs. Hobbs, however, approaching the problem from a different point of view, made the cardinal principle of his explanation active pressure from the outside of each arc. His criticism of Suess was based on his belief that there must be an actual stretching of the strata inside the arc to make possible the outward migration of materials to form the arc. Such an explanation, he believes, must require a noteworthy thinning of the strata in the upper limbs of the overturned folds.[1] If, on the other hand, the active force be directed from without, he believes that the under limbs of the folds (in this case underfolds)

[1] W. H. Hobbs, *Earth Evolution and its Facial Expression*, Macmillan and Co., 1921, pp. 124–26.

should be thinned. As folds with drawn-out upper limbs are not commonly found, Hobbs was led to conclude that the arcuate chains have been developed as underthrusts from without. In an earlier paper he attempted to show that underfolding is easier and more natural than overfolding.[1] To quote: "The active force (thrust) which produces rock folds, instead of operating from behind and above the anticline, as so generally supposed, is applied below and in front. Continuation of the process yields therefore not overturned and overthrust, but underturned and underthrust flexures." Willis, however, contends that overthrusting and underthrusting are determined by local conditions, among which the relative vertical positions of the active pressure and the passive resistance are most influential. If the line of pressure is directed above the resistance, the result is overthrusting. If the pressure be directed below the resistance, underthrusting results.[2]

Experimental results.—In many different experiments on folding in the course of these studies, it was found that either overfolds or underfolds may develop, though not with equal readiness. Apparently some local peculiarities, if of the right sort, may determine which way the fold will turn. These may be in the nature of slight differences in material, unevenness in the thickness of the layers, or a slight initial dip, which in the preparation of the layers is not always easy to eliminate. Variable resistance from the sand on the sides of the blocks of strata, or variability in the overburden, may also be influencing factors. But in a large number of trials such fortuitous variables should tend to eliminate themselves according to the law of averages, and the relative number of overfolds and underfolds should decide which is the more normal type. In these tests overfolds formed in much greater numbers than underfolds. Figure 4 (p. 498) shows the preference for overfolding.

It was found that the nature of the folding can be controlled to a certain extent according to the principle stated by Willis. The layers to be folded were attached to the movable blocks in such a way as to slope upward from the pressure block to the resistance block.

[1] W. H. Hobbs, "Mechanics of the Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 166–81.

[2] Bailey Willis, *Bull. of Geol. Soc. of Am.*, Vol. XXXII (1921), p. 31.

The pressure was thus applied at the lower edge of the gently inclined strata and consequently at a level somewhat below the resulting fold. This arrangement seemingly should favor the development of underfolds. In some cases it did, but in two experiments where an underfold began to develop, an overthrust formed on the steeper limb before the folding became very sharp, and this quickly became the dominant structure with further compression. This order of events seemed very significant, suggesting a strong tendency to overthrust rather than underthrust whenever the opportunity allows. In two other experiments where everything was arranged

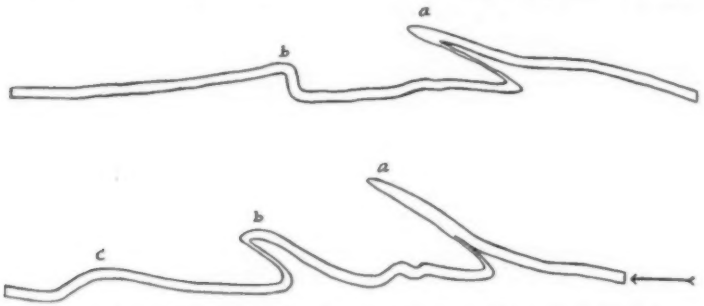


FIG. 4.—Successive stages in the development of overfolds. Top figure after 6 inches of shortening; bottom figure same after 8 inches of shortening. Fold *a* formed first. Fold *b*, which started as an underthrust, has changed into a pronounced overthrust. Note the thinning of the under limbs. With still further compression flexure *c* developed into a strong overfold.

to develop underfolding, overturned folds resulted. On the other hand, when the blocks were placed in the opposite positions, so that the layers sloped downward from the pressure block to the resistance block and the active force was applied somewhat above the fold, no trouble was experienced in developing overfolds.

It was found also that the nature of the materials influenced to some extent the direction of yielding. When the materials were relatively competent and brittle (sand, clay, and plaster), and the mass was deformed by faulting rather than folding, overthrust and underthrust faults resulted in more or less equal proportions. Wedge faults developed in some instances. But in the plastic models it was found almost impossible to produce underthrust

faults. There was, however, one rather unusual case where, in the early stages of the deformation, an underthrust formed on one side of the model and an overthrust on the other side. After further compression the underthrust was truncated by an overthrust and the overthrust cut by an underthrust (see Fig. 16, p. 510).

Hobbs has expressed the belief that overturned folds, though rare, may be developed in special cases (backfolding of anticlines) where the material being folded thins away from the active force.[1] In the experiment by Daubrée which he cites, an overturned fold developed in unmistakable fashion, just as in general there is little difficulty in producing overfolds. Our experience has been that the greater difficulty lies in producing underfolds. To put the case of underfolds vs. overfolds to a more severe test by utilizing this same principle, a layer was prepared to reverse these conditions, by having it thin steadily toward the pressure block. This should have the effect of producing weakness near the pressure block, and seemingly should be most favorable for the development of an underturned fold. Instead of an underfold, the resulting wrinkle was a decided overfold on one side of the model, and a symmetrical upright fold on the other.

From the usual behavior in this series of experiments, it would seem that in the more brittle and elastic materials, where faulting occurs without much preliminary deformation, the fracture may go either way without great preference for the overthrust, but in more plastic, incompetent material, where portions of the mass yield readily to moderate differences of stress and the phenomena are those of folding preceding fracture, overfolding is far more likely to occur than underfolding, and the preponderance of overthrust faulting over underthrust faulting is still greater.

VARIATIONS IN FOLDING

With varying overburden.—To see what effect variations in the amount of overburden would have on the type of folding produced, a series of models was prepared of equal parts of paraffin and vaseline, and of equal thickness. These were deformed at the same rate of speed but with different overburden.

[1] W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. of Geol.*, Vol. XXII (1914), pp. 185–87.

The first model was compressed without covering. Since the material was quite plastic, a high overfold developed. This suggests that horizontal compression near the surface of the earth, where the overburden is not great, would be likely to produce large simple folds, rather than smaller complex folding.

In the second experiment the layer was covered with sand only, so that there were not more than 10 or 15 pounds of total overburden, uniformly distributed over the model whose dimensions were $20''x5\frac{1}{2}''x\frac{1}{2}''$. In this case the folding was more complex. The principal anticline developed nearer the pressure block; did not go so high as in the previous experiment; was subjected to a series of minor undulations; and in addition, a small thrust fault developed.

In the third experiment the overburden totaled 50 pounds, uniformly distributed. In this case the folding did not rise quite so high as in the second, but was more distributed along the length of the model A thrust fault which developed on one side of the model had a greater displacement than that in the second experiment.

In the fourth experiment a weight of 190 pounds was placed over the model. The results of compressing this model were quite different from the others. There was only a very minor amount of folding, but on the other hand, faulting was important, and there was some thickening of the layer. The deformation was not confined to any particular zone.

Thus the general result of increasing overburden was a tendency to produce more complex and more distributed folding, more faulting, and more thickening of the material. Since it is easier for a series of small folds to hold up a heavy covering than it is for one large fold, it is not difficult to see why the folds should not go so high when the overburden was greater. Similarly, in nature, folds should probably be smaller and more widely distributed in depth than at the surface. The occurrence of faults in the specimens where the overburden was greatest is startling, as it is generally supposed that, with increasing depth, folding gradually takes the place of faulting. Faulting, however, is a much easier type of deformation under quick acting stresses than folding, and may therefore be a more natural way of taking up the shortening in cases where the resisting pressures of overburden tend to prevent the upbowing necessary in folding.

But in the earth, where the stresses operate more slowly and the greater length of time allows more extensive readjustment by recrystallization, it is less certain that faulting should increase in relative importance with increasing depth. Down to considerable depths,

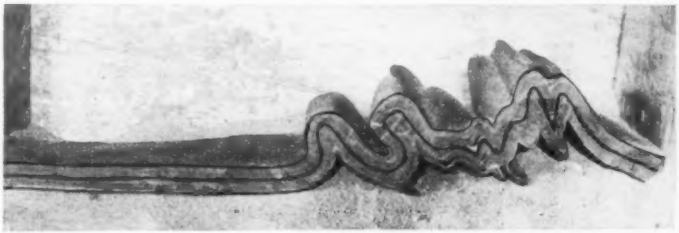


FIG. 5.—Model of six layers. Layers consisted of equal parts paraffin and vaseline except layer 4 (3 par., 1 vas.). Original length 25¼ inches; shortened 9 inches. Ink line follows base of layer 4. Pressure from the right.

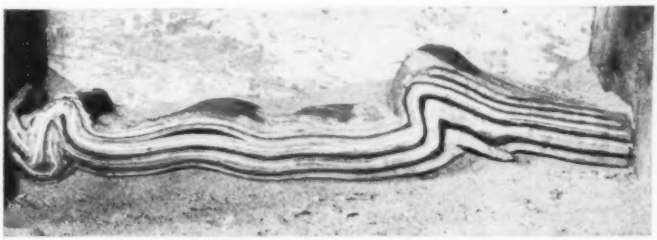


FIG. 6.—Original length 22 inches; compressed 4⅛ inches. Layers 1, 3, 5, 7, 9 and 11 were 1 paraffin, 1 vaseline. Layers 2, 6 and 10 were 1 par., 2 vas. Layers 4 and 8 were 3 par., ½ vas., 1 plaster. Cavity developed under gentlest of the three anticlines. Folds developed first near the two extremities with less deformation in the middle portion. Pressure from the right.

this might be the case, but at still greater depths faulting would doubtless gradually be replaced by the phenomena of rock flowage.

With layers of uniform competency.—In the models having several layers a variation in the folding from the top layers to the bottom ones was generally very marked (Figs. 5–8). Anticlines became less pronounced in lower layers, both when the folding was of the

parallel type, and when there was considerable thickening on the crests of the anticlines. Conversely synclines grew larger with increasing depth, but the change in the case of the synclines was not so marked as in the case of the anticlines. Thus it might appear

FIG. 7.—Same model as Fig. 6, compressed to total of 8 inches. Cavity has disappeared with more intense folding. Other tiny cavities have developed where the folding is gentle. The overturned fold of Fig. 6 has become nearly upright.

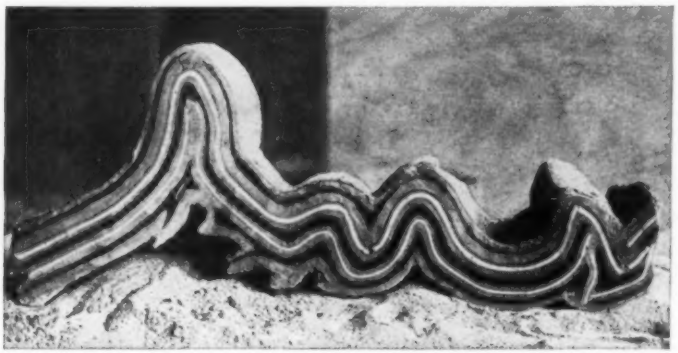


FIG. 8.—Reverse face of Fig. 7 model. Pressure from the left. Vertical variations of folds.

that the shortening was decreasing with depth, but the apparent difference was made up by faulting in the lowest layers. Anticlines which have rounded curves near the upper surface pass into pointed folds beneath. This is one step in the dying out of folds. Slippage between layers has played an important part in the process.

Cavities between the layers of the anticlines and the synclines were most common where the folding was least intense (Fig. 6). It is not certain, however, that this principle can be applied to the location of such ore deposits as the saddle reefs of Bendigo, for there the access of solutions and other factors doubtless play an important part. Pockets of oil and gas should be more abundant where the folding is very gentle.

Competent layers between incompetent.—Experiments were performed in which fairly competent brittle layers were inserted between very plastic layers. The former were made with 4 parts of

FIG. 9.—Original length 25 inches; compressed 8 inches. Layers 1, 4 and 6 were 1 paraffin, 12 vaseline. Layers 2, 3 and 5 were 1 par., 1 vas. Layers 2 and 3 appear as one. Softer layers much distorted. Strangle folds developed.

paraffin to 3 of vaseline, and the latter with 3 parts of vaseline to 1 part of paraffin. It was found that after compression had shortened the models by a few inches, the competent layers folded without much internal distortion, but that the plastic layers were tremendously distorted, being thickened on the crests of the anticlines and in the troughs of the synclines, with much stretching on the limbs (Figs. 9 and 10). In the early stages of folding there was a general correspondence between the anticlines and synclines in the layers of different competency, but, with further compression, the brittle layers developed minor folds which were entirely at variance with the surfaces of the plastic material. This was possible because of the great thickening of the plastic layers whose ready yielding greatly

facilitated the adjustments necessary in this type of folding, and thus constituted zones of accommodation.

In several cases a plastic layer between two competent layers pinched out completely for a short distance. This is comparable to some of the occurrences in the Alps where a layer has been so much thinned that it has completely disappeared from the section. Strangle folds which are also found in the Alps, and in a few other localities, were reproduced in the models (Fig. 9). In some cases the

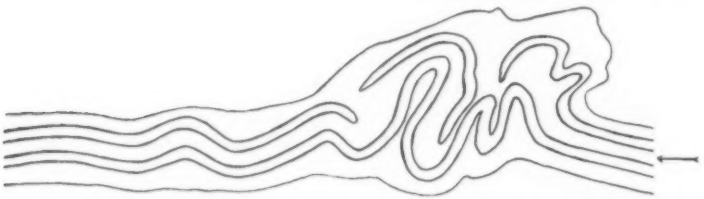


FIG. 10.—Same model as Fig. 9 after 12 inches of compression. The upper competent layer has been pulled apart by upward flowage of the plastic material beneath.

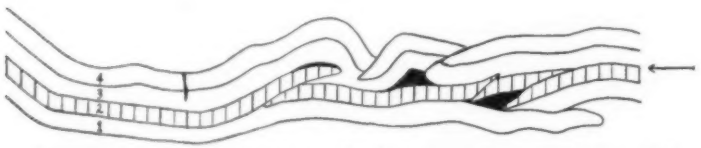


FIG. 11.—Layer 2 made of plaster; other layers 3 paraffin, 1 vaseline; 23 inches compressed to 14½ inches in 30 minutes. Fracturing of the strong layer (No. 2) caused considerable fracturing above and below. Open spaces represented by black. Note the slight degree of folding in the bottom layer.

competent layers were faulted, so that there were two disconnected ends, but the fault was largely obscured because the plastic material flowed in.

Rigid layer in the midst of plastic material.—Where a layer of plaster of Paris was inserted between moderately plastic layers somewhat different results occurred. Since the plaster of Paris was too brittle to be folded, it invariably broke. In breaking it caused considerable fracturing of the surrounding layers (Fig. 11). Conditions of this sort may account for an unexpected amount of fracturing in some types of sedimentary rocks which would normally be more

folded. In one case an anticline developed above the plaster layer and a somewhat fractured syncline below. This behavior was apparently due to a thickening of the intervening plaster by slice faulting. The whole mass was so much broken that it was difficult to trace the individual planes. Such an occurrence might easily cause confusion in an oil field by changing the surface anticline into a syncline below. In general, where an especially brittle formation occurs between more easily folded formations, structural changes in depth are very likely to occur.

ISLANDS OF RIGID MATERIAL

Sedimentation has frequently occurred in seas where islands or submerged reefs of metamorphic or igneous rock have stood above the general level of the sea bottom in such a way that the sediments

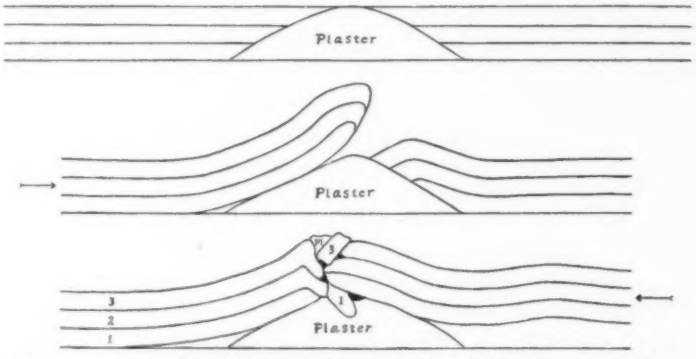


FIG. 12.—Plaster island in midst of weaker beds. Bottom layer 2 paraffin, 1 vaseline; middle layer, 1 par., 1 vas., 1 plaster; top layer, 4 par., 1 vas.

East side of model (middle figure): Beds nearest pressure block turned under and slid upward over the rigid plaster.

West side of model (lower figure): Beds on both sides turned under and sliding upward carried some of the plaster with them.

were deposited all round them, and in many cases eventually covered them. In order to get some idea of what might be the effect of such a buried crystalline mass upon folding which subsequently affected the region, compression experiments were tried upon a model which consisted of a mass of cement with outward sloping sides, placed within a succession of plastic layers (Fig. 12). Compression

of this model caused the plastic layers to be thrust up over the cement block and produced very complex faulting and folding above it. Another way to test the same idea was to place a block of cement in the sand below a portion of a model. The effect of this block was to cause an especially pronounced fold to occur over the block, in spite of the fact that this was placed on the end opposite from the active pressure.

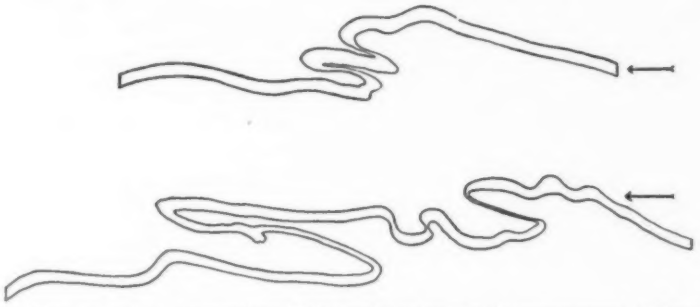
Since in nature there undoubtedly are cases where such former islands of resistant crystalline rocks are not exposed at the surface, it would seem probable that complicated dome structures might be explained in this way. R. C. Moore has reported that folding in eastern Kansas has tended to follow an old buried granite ridge, which formed a sort of island in the later Paleozoic sediments.[1] In a similar way some of the small ranges of central Montana and Wyoming may be due to causes of this sort, and even the Black Hills of South Dakota may owe their origin in part to this selective deformation.

ALPINE OVERFOLDS

Several attempts were made to reproduce the overfolds, or nappes de recouvrement, of the Alps by applying rotational stresses to models in which competent layers were placed between incompetent layers, since this seemed to represent the conditions in the Alps, where competent limestone formations are interbedded with less competent shales. These experiments, however, did not succeed in developing Alpine structures in this way, since the resulting overfolds were overturned only to a small degree, and continued pressure only served to cause folding elsewhere, and to produce a vertical rising of the overturned folds. As it is not easy to see how conditions in the Alps could have been more favorable for producing overfolds than these experimental conditions, one may well wonder at the current European interpretation which assigns such tremendous extents to the nappes. But if low-angle overthrust faulting enters largely into the horizontal shifting of material, these nappes take on a quite different aspect.

[1] Raymond C. Moore, "Buried Granite in Kansas," *Bull. Geol. Soc. Am.*, Vol. XXXIII (1922), pp. 96–98.

A better way to reproduce overfolds was found, though natural conditions do not appear to be so well represented. Single layers consisting of equal proportions of vaseline and paraffin were prepared in long thin sheets whose dimensions were approximately $22'' \times 5'' \times 2''$. By compressing these long thin models, overfolds somewhat resembling the structure sections of the Alps were produced (Figs. 13 and 14). These overfolds had their lower limbs very much drawn out. In at least one case the "tete," or head, of the



FIGS. 13 and 14.—Recumbent folds simulating nappes de recouvrement. These are overfolds whose lower limbs have been drawn out thin. Compare with Hobbs' contention that in overfolds the upper limbs should be thinned.

fold was curved down toward the undeformed portion beyond the fold (Fig. 15).

In some ways these folds were very different from the Alpine folds, as they have commonly been interpreted. According to the standard European interpretation the lower folds were formed first, and were covered successively by more overfolds coming from the south, the direction of the active force. But in these experiments the reverse was always true. The overfolds, as a rule, formed first next to the pressure block, and the later ones farther and farther away. This was in general the earlier experience of Willis.[1] In no case was an overturned fold pushed completely over the one beyond it. By the time that one had been pushed to the point where the

[1] Bailey Willis, "Mechanics of Appalachian Folding," *Thirteenth Ann. Rept., U.S. Geol. Survey*, 1891–92, Part II, pp. 211–82.

under limb was on the point of breaking, another fold formed in front of it, and so on. By continuing the compression sufficiently, faulting took place. In one case (see Fig. 4, p. 498) an underturned fold, which started near the end of the model farthest from the active force, was eventually changed into an overturned fold, due to the advance of the overturned folds from the other end. Such a general tendency and behavior may account for the overfolding being practically all in the same direction in some ranges.

FIG. 15.—Broken overturned fold. The front of the fold has turned under, resembling the so-called head of a nappe. Two nappes in different stages of development formed by compressing a single layer of equal parts of paraffin and vaseline.

Conclusions in regard to Alpine structure which might be drawn from these experiments are, in the first place, that the folds may perhaps have developed in a different order of succession from that commonly inferred, the upper nappes possibly having formed first. Also in the place where one nappe is supposed to have completely overridden another, it is perhaps most reasonable to infer that this was accomplished rather more by faulting than by folding.

DEVELOPMENT OF LACCOLITHIC INTRUSIONS IN FOLDED FORMATIONS

The term laccolith is ordinarily applied to structures in which a fairly thick mass of intruding magma has arched up a dome. While the floor of this structure is rarely seen, it is commonly inferred to consist of more or less flat-lying sedimentary rocks, cut only by the dike or dikes which represent the upward paths of the igneous material. Some of the experiments suggested ways in which a type of laccolith could be produced with folding occurring both above and below the igneous intrusion. In one experiment a thrust fault occurred on the steep side of an asymmetrical fold. This thrust did not cut through the top layer. If some magma had made its way up along this fault plane, it would have tended to spread out beneath the top layer near the top of the anticline. Partial erosion could then have revealed an apparent laccolith. This, however,

would probably be of only modest dimensions, and might be classified as a phacolite.[1]

In another case a wedge fault occurred in the lower layer on the limb of an anticline. Since this wedge faulting took up some of the shortening of this layer, it was not arched as high as the upper layers and thus left a cavity between. In nature, a potential cavity might be produced similarly, and magma, making its way up along the wedge fault, and between the layers, might help force the production of the cavity and fill it. Such an occurrence could also produce a structure which had all the surface appearance of a common laccolith.

Rupture by tension on the crest of an anticline sometimes was confined to the lower layers of a model. In such cases cracks developed right across the individual members in the lower portion of the model. Along these cracks an igneous intrusion could force its way up as far as the unbroken layer and spread out below that layer.

INCIDENTAL OBSERVATIONS ON FAULTS

Dying out of faults.—In nature faults are known to die out upward, downward, and laterally, but it is often impossible to see what happens in the space between where there is a distinct fault and where there is no fault. In the experiments faults of small displacement frequently played out both vertically and horizontally. In some cases the scarp of an overthrust became lower and lower transversely across the model till it disappeared in favor of the unbroken layer. Still more frequently the layers below an anticline were found to be faulted while the top layer was not affected. In another case the top layers were faulted and the bottom layer was merely folded (Fig. 16, p. 510). As sections could be cut into the models at any place desired, it was not difficult to observe the manner in which these faults died out. In general the most common manner was by a thickening and thinning of the layers in such a way as to take up the waste space. A slight local bending after the fashion of a minor monoclinal flexure in many cases facilitated the accommodation. Another method was by the formation of a cavity at the top of the fault on the downthrow side.

[1] Alfred Harker, *Natural History of Igneous Rocks*, 1909, pp. 77–78.

Wedge faults.—The phenomena of wedge faulting occurred rather frequently in the models. These faults, however, were of rather small displacement because it is not easy for the wedges to move for any great distance under the conditions of the experiments without having the whole mass broken across by a general thrust fault.

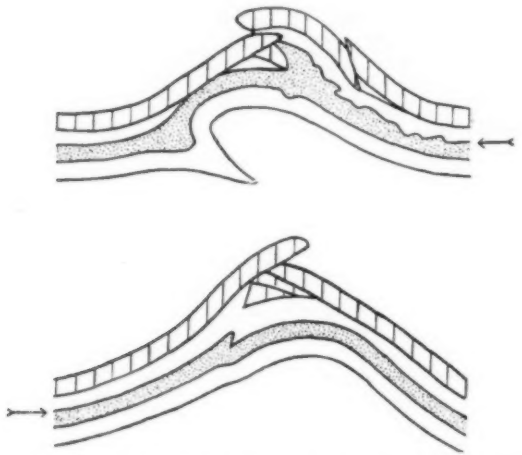


FIG. 16.—Top layer faulted while bottom layer merely folded. Opposite sides of same model. A section cut through the middle of the model showed more shortening in the two lower layers. The nature of the deformation changed rapidly from place to place. Two stages of faulting, an overthrust on one slope and an underthrust on the other; then reversal of the process.

Angles of thrust faults.—In considering the angles of thrust faults, W. H. Bucher in his recent paper on "The Mechanical Interpretation of Joints" lays great emphasis on the plasticity of the deformed material and the depth at which it is deformed.[1] Engineering experiments illustrate clearly that the angle of fracture depends on the nature of the material deformed, and in nature the angle of thrust faulting presumably should be influenced by this factor. If nothing else influenced the angle, low-angle faulting might be found where deformations occurred near the surface and where the formations were brittle. High-angle faults should be

[1] W. H. Bucher, *Jour. of Geol.*, Vol. XXVIII (1920), pp. 707–30, and Vol. XXIX (1921), pp. 1–28.

found in the less brittle materials deformed at greater depth. Field observations only in part substantiate this idea. Since the mechanical principle is doubtless correct, the anomalies must be explained. Some suggestions as to the cause of high-angle faulting were obtained from these experiments on folding.

High-angle thrust faults.—By using layers of paraffin and vaseline, which would fold before breaking, thus representing the conditions of folding not far from the earth's surface, fairly numerous high-angle faults were developed. The conditions determining these steep faults were found to be somewhat varied. In one or two cases a crack developed in the upper side of an asymmetrical anticline, due to tension, and this crack changed into a thrust fault with its dip well over 45° (Fig. 17). Secondly it was found that high-angle thrusts may develop on the limbs of anticlines. In such situations the transmitted forces operate nearly parallel to the sloping surface of the limb, and therefore should a fault develop at 45° to the applied forces, it may be inclined as much as 90° from the horizontal. In several cases a fault developed on the side of an anticline, and as compression continued, the fault ceased to grow, while the anticline became more tightly folded. In such cases the angles of the faults were low at first, but gradually increased as the sides of the anticlines grew steeper, and in one case they approached verticality.

FIG. 17.—Break thrusts on stretched lower limb of anticline. The higher up on the fold, the steeper the angle of fracture. Thrust near crest has angle of 57°.

Low-angle thrust faults.—In the other direction the very great potency of rotational stress in lowering the angle of thrust faulting even down to horizontality, as exemplified in the great overthrusts, has been pointed out by the senior author in a paper on "Low Angle Faulting."[1] This rotational stress may be developed in a variety of ways.

Faulting in sand and clay.—While testing the qualities of the sand used in enclosing the models, in order to determine what effect they would have on the deformation, some rather surprising results came to light. A layer of dry sand 3 inches thick, with flattened

[1] R. T. Chamberlin and W. Z. Miller, *op. cit.*

surface, was placed in the bottom of the compression box. After pushing the end of the sand forward for about 1 inch, a terrace-like development was produced whose scarp appeared about 5 inches from the pressure block; 2 inches of pushing produced a second terrace scarp 3 inches farther out, the terrace being correspondingly uplifted; 4 inches of compression developed a third terrace 1 inch in width. With further pressure the entire mass moved forward.

The cause of these terrace-like uplifts was investigated in several ways. Straws were stuck into the sand between the pressure block and the zone where the first terrace was expected to begin. Upon applying pressure it was found that those straws which were stuck deeply into the sand were bent over away from the pressure block, while those straws which extended but little beneath the surface remained upright. This difference in behavior suggested that the upper portion of the sand moved forward largely as a unit over the lower portion after the manner of thrust faulting in solid blocks.

The nature of this deformation was further tested by placing smoked glass plates in the sand at right angles to the pressure block. In this way some idea could be obtained both as to how much of the sand was moved by the terracing action, and also its direction of movement, because the moving sand rubbed against the plates and removed the soot in streaks. The results of this method were not always very satisfactory, but some cases showed clearly that there had been thrust faulting with the dips of the slippage, as indicated by the movement of the sand grains, ranging from 20° to 35°.

Clay was substituted for the sand and pushed in the same manner. Similar terraces also developed in this material. Since clay will stand in slopes better than sand, sections were cut in it with a knife at right angles to the terraces. In this way the actual fault planes could be observed for a short time, till the clay broke off and covered them. The angles of these faults varied from 9 to 29 degrees. In general the angle seemed to become lower after faulting had progressed for a little distance.

This thrust faulting in sand and clay suggests that some of the escarpments found in unconsolidated mantle rock in the basin ranges of Nevada and Utah may have been the result of thrust faulting rather than normal faulting.

REVIEWS

British (Terra Nova) Antarctic Expedition, 1910–1913. Glaciology. By C. S. WRIGHT AND R. E. PRIESTLEY. Quarto, pp. xx+487, figs. 481, plates 417, maps XIV. London, 1922.

This important work is the joint product of a physicist, C. S. Wright, and a geologist, R. E. Priestley. The chapters on "Snow and Its Derivatives"; "Ice Crystals Formed from Vapour"; "Crystalline Structure of Ice"; "The Mechanism of Glacier Motion"; "Ablation and Thaw, with Particular Relations to Antarctic Glaciers"; and "A Review of the Causes of Glacierisation" were written by Wright. Those on "Classification of Land-Ice Formations"; "Structure of Glaciers"; "The Antarctic Icefoot"; "Antarctic Fast-Ice"; "Antarctic Pack-Ice"; "Antarctic Icebergs"; and "Geological Climates of the Antarctic" were prepared by Priestley, and that on "Ice Formations Characteristic of an Advanced Stage of the Glacial Cycle" by the two jointly. This division of labor necessarily implies some degree of independence of work and of textual treatment, but just how much can probably best be learned from the text itself. A general concurrence of views is claimed. The reader will do well, however, to note the authorship of each of the chapters as he reads them, for he may find that one sees through the spectacles of the laboratory, the other through the binoculars of the field. The studies actually made are, in the main, regional (Victoria Land), but the treatment has wisely been given continental breadth by comparisons between all known parts of Antarctica. There is thus brought together a vast amount of material relative to the glacial phenomena of a great region only imperfectly known heretofore. It will only be possible to notice a few of the more outstanding features. We shall therefore feel at liberty to disregard the order of subjects and touch as most convenient the themes of most concern to students of geologic climates.

As a background for more special subjects, let us first notice a tabular summation of what are held to be the known glacial periods of geologic history (p. 418).

Some glacialists would add to the periods listed and some would perhaps question certain periods included, but the table seems to fairly represent the weight of competent opinion. The main things to be

emphasized are that they range over almost the whole of known geological history (Proterozoic to Pleistocene) and that the intervals between them are much greater than the glacial periods themselves. There follows this table a summary of what is now known of the geologic climates of Antarctica (p. 419) the gist of which is here given because of its special interest.

TABLE OF GLACIAL PERIODS

Main Proved Glacial Periods	Local Glaciation	Countries Where Developed	Remarks
1. Huronian		Canada	Pre-glacial surface an undulating surface of low relief.
2. Proterozoic		India Africa Norway	Possibly two separate glacial periods combined. In Norway probably low land as pre-glacial surface.
3. Proterozoic or Lower Cambrian		China Australia	Middle latitudes N. and S. of Equator. Australian geologists claim this Ice age in Australia as Lower Cambrian; United States geologists insist that here also it is Proterozoic.*
4. Devonian		South Africa	
5. Permo-Carboniferous		Australia S. Europe Brazil Africa India	Middle to low latitudes. Seasonal climate in N. and S. Marked inter-glacial periods. Developed on plateaux of low relief and mountains not particularly glaciated.
6.	Cretaceous		
7. Pleistocene		World-wide	Particularly effective in high latitudes. Several inter-glacial periods. Chiefly developed on high plateaux. The only glaciation yet proved in Antarctica. Apparently began there in Eocene or Oligocene times, and has been interrupted by inter-glacial periods.

* Information has recently been received from Australia to the effect that Professor David, who has re-examined the exposures, now agrees with the United States geologists in their view of the Proterozoic age of these deposits.

Respecting the climates of the pre-Cambrian ages little evidence has been found in Antarctica. The presence of limestone and graphite seems to imply at least moderate warmth at the specific stages they represent,

but of course not necessarily of all stages of the terranes in which they are found. Erratic blocks of sandstone containing Radiolaria perhaps imply the same.

In Cambrian times, limestone with Archaeocyathinae and calcareous algae are found in widely separated localities. "Huge reefs of coral and algae living in association—much as the coral reefs of today, but probably of even greater size—must have existed through some degrees of latitude at least." "The occurrence of the Archæocyathinæ and Epiphyton on a large scale in Cambrian Antarctic seas is (if any faith may be placed in the principle of the elucidation of past climates by analogy with the conditions under which the present allied faunas of the world flourish) definite proof of a fairly high temperature in the Cambrian Antarctic seas" (p. 422). "Yet, it must be admitted, a comparison between Antarctic and Australian forms of Archæocyathinæ brings to light the fact that all Antarctic forms yet discovered are either embryonic or dwarfed. They bear the stamp of having had to struggle for their existence in rather an unsuitable environment" (p. 423).

Respecting the climate of Silurian times, no reliable information is reported. Fish identified as Devonian have been found in shales, but their climatic import is not regarded as decisive, except in a rather broad sense.

The most interesting of all Antarctic formations climatically is the Beacon Sandstone, and fortunately it is the one most widely exposed in South Victoria Land. It contains a relatively large quantity of woody or carbonaceous matter or of imprints, including plant fossils and beds of coal. These are distributed through a considerable thickness of the formation. "The type plant of the Glossopteris flora has been discovered in great abundance at the Beardmore Glacier, within a few degrees of the Pole. There can be no doubt at all that, throughout a considerable portion of this time, the climate of large regions of this part of Antarctica was such as to favor the development of a relatively prolific flora, though one of a type which is associated in other countries with evidence of the great Permo-Carboniferous glaciation" (p. 424). As is well known, Antarctica is regarded by many as the original center of distribution of the Glossopteris flora. According to this view the formation in Antarctica was at least as early as the glacial formations of Australia, India, South Africa, and South America, which also contain the flora.

An ample Jurassic flora was found by the Swedish Antarctic Expedition at Hope Bay in West Antarctica and identified by Gunnar Anderson and by Nathorst. From the climatological point of view, it is said the collections might have been gathered on the coast of Yorkshire.

Marine formations of Cretaceous age were found in West Antarctica and Graham Land by the Nordenskjold Expedition, containing fossils identical with those of the same age found in India.[1]

The occurrence of dicotyledons in marine sediments of Oligocene or early Miocene age, in West Antarctica, seems to imply a temperate climate, but this evidence and that of the associated marine fossils are thought to be not altogether decisive. "Considering all the evidence together, we are perhaps justified in visualizing conditions similar to those at present existing near the outer limits of the temperate zones of to-day, though the presence of some 50 sub-tropical forms and only twenty temperate forms in the flora suggests a somewhat warmer environment" (p. 433). The possible existence of glaciation farther south at these or earlier times (Eocene) is suggested, but the weakness of the grounds for the suggestion is also noted.

Late Tertiary time in Antarctica is said to have been characterized by great eruptions of volcanic material. At three localities in this region true erratics occur, from which, as also from supporting evidence of other sorts, it is inferred that glaciation was present during some part of this time.

The evidence bearing on the initiation of the present climatic state is said to be less complete and satisfactory than could be desired. It cannot well be sketched briefly, and the reader is referred to the details offered.

In summation, it is inferred that, incomplete as the record is, it "is eloquent of the fact that, to all appearance, any *glacial conditions have been the exception and not the rule in Antarctica.*" This conclusion, the reviewer believes, is in general harmony with the testimony of the geological formations within the Arctic Circle, where the stratigraphic and paleontologic evidences are more ample and explicit. Now that this mass of evidence from the South Polar circle has been piled upon the still greater mass of similar evidence, long known, from the North Polar region, as well as the important new testimony added recently by Lauge Koch[2] and A. C. Seward,[3] there ought to be no longer any disputation over the former existence of warm climates in polar latitudes for long periods between the known glacial periods.

[1] The authors fail to cite the evidence of similar import found in a collection of fossils made by the artist Stokes and determined by Stuart Weller, *Jour. Geol.*, Vol. XI (1903), pp. 413–19; especially p. 414.

[2] Lauge, Koch, "Stratigraphy of Northwest Greenland," *Meddelhena fra Dansk Geologiske Forening*, Bd. 5, No. 17, 1920, and later papers.

[3] A. C. Seward, *A Summer in Greenland*, Cambridge University Press, 1922.

If next we look over all the outstanding features of Antarctic glaciation, as set forth in this report, in an endeavor to catch the one which, aside from superior dimensions, most distinguishes it from the glaciations of the Arctic regions and the high altitudes of mid-latitudes, we think it will be found in the great display of *the initial and growing stages* of glaciation, as distinguished from *the mature and vanishing* stages. There are unparalleled snow-fields and névé-fields; and great displays of the lower orders of solidification of the glacier type; but the higher orders of compact glacier ice are remarkably scant. A part of the explnaation is well recognized, though perhaps not emphasized as much as it might well be. The collecting grounds are large, the mean slope is gentle, the average temperature low, melting almost absent, consolidation by granular growth slow in the absence of much water, and the mean motion meager, so that, before the great mantle has reached a highly compacted stage and entered upon much forceful shearing work, the sea level is reached and the partially solidified mantle is floated away in the form of great tabular icebergs. These are so porous in appearance that they are sometimes called "snowbergs." This term overstrains the facts of the case, but it helps correct the intimation that Antarctica displays the full cycle of a typical glacier. We shall have occasion to return to this in reviewing the subjects of glacial structure and glacial motion. Antarctica tells with wonderful impressiveness the story of a glacier's birth and early growth, but the story is cut off in early youth before the stiffer work of the glacier's maturity has begun. Some of the overenthusiastic expressions of the authors about the superior instructiveness of Antarctic glaciation need to be qualified by emphasizing Antarctica as a field of surpassing opportunity for the study of snow and snow-fields, of névé and névé-fields, of icebergs, and of sea-ice, but by emphasizing also that it falls far below the Arctic lands and some mid-latitude tracts in facilities for the study of the more solid phases of glacier ice and that forceful shearing action which grinds rock-flour, scores imbedded material and the glacier's bed, and thus leaves the distinctive marks by which ancient glaciations are chiefly identified.

In view of the unparalleled resources of the Antarctic field for the study of snow and névé, it was both natural and appropriate that the early chapters of the report should center on the formation of snow crystals, their growth into the granules of the névé, and the transition thence into glacier ice. It is natural also for the reader to expect, in view of the opportunity, a discussion of the growth of granules of snow into névé and of névé into glacier ice of like high order. In most respects this expecta-

tion is realized so far as the observational phases of the subject are concerned. The special studies in this line cover a wide range and much new matter is added to previous knowledge. In extending the treatment, however, to generalizations and interpretations involving past work and previous views, there appear some strange misconstructions. As these take the form of statements leading up to new interpretations in such a way as to form their background and basis, they require notice to forestall confusion respecting the main subjects. For example, in the approach to a new explanation of the growth of snow granules, the following statement is made:

> In the Antarctic (as elsewhere), where a snow-drift or other mass of snow crystals persists for a certain time, a change occurs in the size and shape of the individual crystals, this change (at least within certain limits) being progressively toward an increase in the mean size of the crystal. Broadly speaking, this modification probably takes place by the elimination of those crytsals which are of least size, and by the addition of their mass to the larger crystals. . . . . This dependence of the rate of change upon the temperature is supported by laboratory experiments,* and from laboratory experiments we also know, at least for temperatures slightly below freezing point, that the rate of the change increases with the pressure applied.† These two facts have given rise to the theory that the growth of certain crystals at the expense of others takes place only when the snow or ice is close to the melting temperature [pp. 45–6].

This last statement has the force of an intimation that the growth of snow crystals much below the melting point was not a factor of previous views and that these left an unoccupied field to be exploited. But this intimation is quite far from the truth. In the paper of Chamberlin, cited as giving experimental evidence of granular growth, it is said (pp. 193–4):

> The microscopic study of new-fallen snow reveals the mode of change from flakes to granules. . . . . If measured systematically from day to day, the larger granules taken from beneath the surface of coarse-grained snow are found to be growing. In a series of experiments to determine the law of growth, it was found that when the temperature of the atmosphere was above the melting point, the growth was appreciably more rapid than when the air was colder, but that there was, on the average, *an increase under all conditions of temperature.*

The italics are those of the paper cited, which was written twenty years ago. The basal fact thus demonstrated and emphasized has been

* T. C. Chamberlin, "A Contribution to the Theory of Glacial Motion," p. 193, Decennial Publication. University of Chicago, 1904.

† Hess, *Der Gletscher*, p. 31 *et seq.* *See also* Appendix to the report. [Footnotes the author's].

extensively taught ever since, at least in America. The microscopic examinations of the granules referred to were carried out by C. S. Peet and E. C. Perisho daily throughout the rather severe winter of 1893–94 as experienced at Chicago. The granules and their whole immediate environment were often much below the freezing point for days together. Furthermore, in the paper cited, there was also a discussion of the effects of the penetration of the snow fields by the "winter wave" of the arctic region, and mean temperatures as low as $-25°$ C. were had under consideration. But disregarding these explicit postulations of granular growth at temperatures far below the freezing point, the writer of this part of the report continues:

> The supposed mechanism seems to be a progressive melting under pressure where the points of the crystals touch one another, and a flow of the fluid thus produced to other places where the pressure is less. This might afford a reasonable explanation of the cause of growth of the larger crystals at the expense of the smaller in a mass of snow composed of individual crystals at temperatures near the triple point, for the local pressure per unit area must be greater for the smaller crystals, and therefore a greater amount of melting should take place at their surface. It does not, however, afford any explanation of the fact that crystals do slowly grow in size, even at temperatures well below zero Fahrenheit, where the pressure due to the superincumbent foot or so of snow is utterly insufficient to cause any significant local increase of pressure.

The theory of yield and growth by pressure-melting at points of contact has long been held for the range of temperatures to which it is applicable but not urged, so far as we know, for any other. As growth at lower temperatures of any degree had long been assigned to evaporation and re-accretion, the last sentence has no pertinence except for the author's unwarranted predication of the view "that the growth of certain crystals at the expense of others takes place *only* [italics the reviewer's] when the snow or ice is close to the melting temperature."

The reviewer, at least, had never previously heard of a theory of granular growth so restricted. On the contrary, the following from Chamberlin's paper above cited has had much currency:

> To follow the process [of granular growth] it should be noted that the surface of every granule is constantly throwing off particles of vapor, that the rate at which the particles are thrown off is dependent, among other things, on the curvature of the surface, being greater the sharper the curve; that the surfaces of the granules are at the same time liable to receive and retain molecules thrown from other granules; and that, other things being equal, the retention of particles also depends on the curvature of the surface but in a reversed sense, the less curved surface retaining more than the sharply curved one. Under these laws,

it is obvious that the larger granules of smaller surface curvature will lose less and gain more, on the average, than the smaller granules of greater curvature. It follows that the larger granules will grow at the expense of the smaller [p. 194, "Contribution to the Theory of Glacial Motion," T. C. Chamberlin, 1904, the paper cited by the writer of the report].

In following the further discussions of the growth of snow granules, the non-technical reader is quite sure to become bewildered by the substitution of the concept of *vapor pressure over the individual granules* for that of *evaporation*, in the author's citation and criticism of views written years ago, especially in the absence of any explicit statement of the sense in which the term "vapor pressure" is used; for example:

> As regards the increase in mean size of the crystals, this, as has been pointed out by Chamberlin,[1] should be carried out through the growth of the larger crystals at the expense of the smaller ones, *the action taking place for the reason that the average vapour pressure over a small crystal is greater than that over a large crystal.* [Italics the reviewer's.]
>
> Several passages in Chamberlin's treatise are, however, obscure. Thus the increased vapour pressure over a small crystal is said to be due to the increased curvature of the surface, as is the case with water drops [pp. 118–19].

This is certainly taking extraordinary liberties in citation and in making the mutilated citation the basis of criticism, for no mention whatever is made of vapor pressure in the paper cited. A higher rate of evaporation was assigned to sharper curvature. If the substitution of vapor pressure for evaporation is intended to mean that vapor pressure and evaporation are the same thing, it seems as though that should have been so stated explicitly. Perhaps the reader would like a chance to see for himself whether the obscurity grows out of the original point of view or the substitute.

The need for an explicit statement of precisely what is meant by vapor pressure over the individual granules becomes the more obvious when the ordinary use of vapor pressure comes into use as it does later in giving a list of vapor pressures (p. 267). No hint that another sense of the term "vapor pressure" is here given, but it is evident from the context that the vapor pressures listed are the familiar partial pressures of the water vapor of the atmosphere which are pressures *upon* the granules actuated by the attraction of the mass of the earth.

[1] T. C. Chamberlin, "A Contribution to the Theory of Glacial Motion," Decennial Publication. University of Chicago, Series I, 1904, *Geology*.

Putting aside all special and technical senses of the term "vapor pressure," the facts of the case seem to be these:

If a granule of snow be placed in a suitable receptacle whose inner surface is such as to throw the evaporated particles back, an equilibrium state between the thrown-out and the thrown-back will be reached in time. In this state *neither growth nor depletion takes place.* The out-throw (evaporation) of a small granule with a high curvature is greater than that of a large granule with low curvature. When, therefore, the small granule is shut up by itself in a receptacle until it attains equilibrium, it develops a higher throw-back; i.e., a higher vapor pressure about itself, than does a large granule of less curved surface. But looked at in this way, it is seen that it is the relative evaporation that is the *actuating agency* and that it is the *superior evaporation* of the small granule of higher curvature that gives it the higher vapor pressure when it is suitably *confined.* The vapor pressure is merely a *secondary* effect and is dependent on the *confining contrivance.*

If a granule be placed in a perfect vacuum of unlimited extent—the open sky would be an admirable illustration if the atmosphere about the earth were absent—no such vapor pressure on the granule would arise.

If, instead of either of these ideal cases, we consider the most common of actual cases—that of a granule within a layer of snow—we find it surrounded by the interspaces between itself and its neighboring granules. These interspaces are more or less affected by the varying pressures of the wind and the states of the barometer, and are directly affected by the evaporation of all the granules opening upon them. Out of this complexity let us select for illustration the simple typical case of a large granule opposite a small one. The latter evaporates faster than the former. The first effect then is that each granule receives the particles thrown off from the other, i.e., the large granule receives more granules thrown off by the small granule than the small granule receives from the large granule. After the first action there follows an indefinite series of secondary actions of the to-and-fro type which give rise to a common vapor pressure to which all the other granules opening on the cavity also contribute. This common pressure is controlled ultimately by the gravity of the earth and becomes a factor in the partial pressure of the vapor of the atmosphere. Taken as a whole, it is thus clear that the process of growth under these conditions is primarily that of evaporation and re-accretion, and in this the small granule loses most on the average and gains least. The special vapor pressure on the surface of

the individual granule can scarcely be said to have developed at all, and in so far as it is developed it is a *secondary* product and is so uncertain and elusive as to be beyond tangible evaluation.

If the conveniences of the laboratory have developed technical senses of common terms, that does not abolish the common English of mankind and this should be used in giving great results to the world. Certainly terms of special sense should not be incorporated in literature two decades old.

In treating the phase of granular growth due to melting under pressure, the writer of this section of the report urges the limitations of pressure that may possibly arise in glaciers by reason of their weight as though that were the sole source of melting pressure in Chamberlin's view, and an objection to it (p. 119), whereas, in common with others, he assigned the melting pressure in very explicit terms chiefly to the concentration of stress felt at the point of a granule under pressure which touches another. The intensity of this pressure depends on the ratio of the area of this point of contact to the area which concentrates pressure upon it. Theoretically, the concentration may be indefinitely large. Its actual amount undoubtedly varies through a wide range. The principle is impressively illustrated in the cutting of deep grooves in the rock floor of glaciers.

The singular thing in all this strange treatment of old views is that after all the views advocated in the report are closely similar to those beclouded.

There are some other vital phases of doctrine over which the text prepared by C. S. W. throws similar obscurity or misleading intimations but space does not permit their review here. It is only fair, however, to say explicitly that nothing of the kind has been found in the text prepared by R. E. P.

It has already been remarked that this report gives ample evidence of the superior richness of the Antarctic field in material for the study of the initial and earlier stages of glacier formation and action. One of the quite striking phases on which it would be worth while to dwell, if there were time, is the softness of the snow field near the pole even when the snow appears to be somewhat old. Amundsen reports that he was able to push a tent pole into the snow surface to its full length of 6 feet without difficulty. This seems to imply slow solidification and relative freedom from driving wind action, which solidifies the surface by driving snow spicules into the interstices. It is thus highly suggestive as to conditions at the pole. Of somewhat similar significance is the condition of the upper

snow layers of certain parts of the Ross Barrier, which is practically at the sea-level. The snow particles are said to remain angular for two or three years, which contrasts strongly with the rapidity of snow granulation in warm and moist lands. These and other phenomena of like type clearly show that the processes of granular growth and glacial consolidation sometimes at least proceed with surprising deliberateness. With little doubt, this is due rather to the *persistence* and *continuity* of the coldness and dryness of the region than to any special intensity of these, though they seem to be remarkably intense at times.

In contrast to the unsurpassed display of the snowy, névé, and earlier stages of glacierization, Antarctica offers only an exceedingly scant exhibit of the later and more solid phases of glacier development, particularly those associated with the more forceful and distinctive work of glaciers, such as the bruising, scoring, grinding, and polishing of rocks. Some little emphasis has already been laid on the fact that the sea cuts off what might otherwise be the later glacier history of the main Antarctic ice mantle and substitutes floating careers as derivative icebergs. But this spectacular change, great as it is, does not seem to represent the whole truth, for not a few Antarctic glaciers end on the land and it might be expected that these would take on the same features and activities as the short glaciers, or glacial tongues, in similar latitudes in the Arctic region. A comparison with the latter, in almost identical latitudes, shows that the two are markedly different. In both cases some of these are tongues of the main ice-caps, while some are independent local developments. In the Arctic region the rule is vigorous action in the form of rock-scoring and the development of schistose structure in basal portions of glaciers with abundant insheared débris of all sorts and sizes. In Antarctica, according to this report, such evidences of vigorous forceful action are singularly scant. This appears very fully and explicitly in the chapter on "Structure of Glaciers" (R. E. P) (pp. 223 ff.). Striated bowlders, grooved and planed glacier bottoms and sides, rock-flour, and true subglacial till are almost absent; indeed they are even conveniently spoken of as simply absent. The schistose structure and insheared glaciated material, so wonderfully displayed in the vertical sides and ends of the glaciers of the corresponding Arctic region—particularly about Inglefield Gulf—seem from this report to have no really parallel development in Antarctica. There is, indeed, some banding and "silt layers" in the lower parts of some of the glaciers, but in only one or two cases do the authors find evidence which permits the supposition that the silt could have come from the bottom (see pp. 230–31). Silt layers of surface

origin, as well as layers of coarse débris derived from cliffs, are fully described, but no insheared layers of mingled glaciated material ranging from rock-flour to great striated bowlders are described. From the causal point of view, this is a matter of the utmost importance, for this kind of work is *glacier work par excellence*. But this review has already grown so long that, most interesting as this is, it cannot be discussed here.

The book closes with "A Review of the Causes of Glacierisation" (C. S. W.) (pp. 463–70). As the climax of a discussion of glacierization of the colossal Antarctic type, this dwells too long on causes of climatic variation whose known cycles are so short as to need to be multiplied thousands or ten thousands of times to fit the glacial types, and not long enough on the necessity of selecting causes whose cycles are of the same order as those of the great glacial epochs themselves. Objections to such putative causes, of course, presented themselves. From these the discussion leads up (or down) to the suggestion that the theory of Wegener, if tenable, might solve some of these difficulties. The reader may perhaps sympathize with the reviewer in wishing he had closed the book before he reached this anticlimax. But, without disguising the fact that the report limps badly at times on one of its legs, it is nevertheless a contribution to glaciology of a very high order of value.

T. C. C.

Geology of the Tertiary and Quaternary Periods in the Northwest Part of Peru. By T. O. Bosworth. London: Macmillan and Co., Ltd., 1922. Pp. xxii+434, pl. 26, folders 11, fig. 150.

This volume constitutes a very notable contribution to the geology of South America. It is a departure from the reconnaissance reports of large areas which constitute so large a part of the pioneer geologic literature on South America, inasmuch as it reports in considerable detail and in thoughtful and painstaking fashion careful geological observations within a comparatively restricted area.

The area described is a strip of arid territory twelve to fifteen miles wide, lying between the westernmost range of the Andes and the Pacific Ocean, a short distance south of the Ecuador boundary. The Amotape Mountains to the east, 3,000 to 5,000 feet high, consist of Cretaceous and Paleozoic rocks. From them a great "breccia deposit," or peidmont alluvial plain, slopes westward onto a series of three pebble-covered raised sea beaches, called Tablazos, which constitute plateaus stepped up from sea-level to an elevation of 1,100 feet in the highest. Tertiary

rocks are exposed west of the mountains, where rapid erosion has cut through the breccia fan and tablazo deposits.

The Tertiary rocks are chiefly shales, with subordinate sandstones: the Zorritos formation, 5,000 feet thick and more, Miocene; the Lobitos formation, 5,000 feet plus, and the Negritos formation, 7,000 feet plus, both Eocene. They are of shallow-water origin, and their deposition, in view of their great thickness, was probably accomplished by subsidence of the sea bottom at intervals. These rocks are not folded; but close faulting has broken them into blocks, tilted in different directions, and at angles of 5° to 35°. This has been done by Andean upwarpings, in such a manner that this coast strip constitutes part of a "crush belt" along a geo-fault, the axis of which is believed to be in the Pacific Ocean at the edge of the continental shelf.

After this faulting there was a long period of erosion, with later submergence. In Quaternary times, a series of nearly vertical movements took place in which the Andes Mountains acted as a hinge, the free edge being the Pacific fault. There was a series of four episodes, beginning in each case with a marine transgression, the cutting of an extensive marine erosion plane, and the deposition of marine beds upon it; and terminating with an uplift, which elevated a plateau-like sea floor, or tablazo. The oldest and highest of these tablazos now stands at an elevation of 1,100 feet above tide, the ancient cliff line being only one or two miles from the foot of the Andes. The lowest and latest is now in the phase of emergence, giving partially flooded coastal plains.

The tablazo deposits consists of loosely compacted shell limestone, with large pebbles locally. This peculiar type of sediment is explained by the fact that no streams enter the ocean for 140 miles along the coast, except during the floods which occur twice or three times in a century; the accumulating calcareous material being free from clastics except at such times.

After the uplift of the first of these tablazos, exposing a large flat surface at the foot of the mountains, the floods from the latter aggraded great piedmont alluvial "breccia fans" on the tablazo; and the subsequent cutting back of streams into the latter gave terraces in the alluvium. With the development of the succeeding tablazos, similar aggradation and subsequent terrace cutting occurred in connection with each.

The author draws some interesting conclusions from his field observations as to the length of time, concluding that not one ten thousandth part of Quaternary history could have taken place within the last 500 years. This conclusion is based upon the hundreds of feet of observed

diastrophic movement in Quarternary time, the several retreats and advances of the sea, with the cutting of cliffs ten to twenty miles inland each time; the deposition of hundreds of feet of limestone between uplifts; the carving of deep valleys in the terraces back from the sea; and the fact that while the cycle of coastal movements is still in operation the amount of movement has been imperceptible in historic times (since the time of the Incas).

He points out peculiar conditions and processes in the desert at the present time. The work of the sun, slicing the pebbles of the alluvial deposits into thin angular fragments, is shown. The facetting of pebbles by the wind is a common feature, and is carried to the point where, of the original pebbles, small splinter-like fragments alone remain. A type of stream-lined topography developed by the wind is described. A discussion is given of the sand dunes of the area, in which he presents instructive observations and ideas, stressing the location and shape of dunes as influenced by their function as a filler for dead air space. The discussion of crescentic dunes is of particular interest.

A section on the Paleontology of the Tertiary formations by Messrs. Woods, Vaughan, Cushman, and Hawkins is the only part of the volume not contributed by the principal author. The Negritos fauna is correlated with that of the Wilcox and Lower Claiborne groups of the Gulf Coast Eocene; and is also stated to resemble Alpine, French, and English Eocene faunas, pointing somewhat to an Eocene trans-Atlantic ocean, with northern and southern shore-lines. The Lobitos fauna is called upper Eocene, in part at least. A number of excellent plates illustrate the detailed description of the different species.

The section on the petroleum geology stresses the lack of anticlinal structure, and the absence of oil except in the Tertiary. Surface indications of oil are abundant, such as oil seeps; oil-bearing mud volcanos; petroleum odor, of sandstones particularly; and the presence of petroleum on the sea near by. A large part of the total Tertiary section is productive at one horizon or another, although few of the sands are continously traceable laterally. Their productivity is highly variable, probably because of the extensive faulting; resulting in moderate sized wells over a large area. There is little or no underground water.

The character of the oil, which is dark to greenish brown, mixed base, and chiefly from .81 to .85 specific gravity (43.2–35 Be), changes near the old shore-line at the foot of the Andes, where it becomes heavier and more asphaltic. In general the oil gives 15–35 per cent of distillate at 150° C.; 30–50 per cent at 150–300°, and good lubricants from the

remainder, the lubricants from some of the oils showing a notably low solidifying point.

The most important fields are the Zorritos, Lobitos, Negritos, Cabo Blanco, and Lagunitas. The district described produces more than 99 per cent of the total Peruvian output, and about .5 per cent of the world's annual supply. Seventy-five per cent of the product is controlled by the International Petroleum Company of Toronto (an Imperial Oil Company subsidiary), and about $22\frac{1}{4}$ per cent by a British company (Lobitos Oilfields, Ltd.).

The reviewer found the volume enjoyable to read because of its large print and abundance of headings, as well as the good diagrams, maps, and illustrations. There is not a little repetition of the subject-matter, not all of which seems unavoidable, or desirable for clarity; but the book is highly interesting and instructive, both for the general geology of this unusual region, and the petroleum geology of the important oil occurrence.

T. B. R.

Untersuchungen uber die Tektonik der Lessinischen Alpen und über die Verwendung statistischer Methoden in der Tektonik, I. Teil. By J. Pia. Denkschriften des Naturhistorischen Museums in Wien. Band 2. Geologisch-Palaeontologische Reihe 2. 1923. Pp. 229, pls. 5, figs. 61, tables 86. (Price $4.80. Orders to be addressed to Geologische Abteilung des Naturhistorischen Museums, Wien I. Burgring 7.)

The first chapters of this book are devoted to a detailed tectonic description of the mountains situated between the rivers Etsch and Brenta, from the Sugana Valley on the north to the plain of Venice on the south. The folds of this region are very slight in comparison with the rest of the Eastern Alps. They show more or less distinctly the character of knee-bends. They are crossed by a richly developed system of faults, mostly directed toward NNW. The description is illustrated by a table of sections and by a tectonic sketch-map.

The second part of the book is of more general importance. It deals with an attempt to adapt statistical methods to tectonic descriptions, which may enable us to describe in a more accurate way the direction and intensity of folding in different areas. The leading idea of the method described by Dr. Pia is to divide the compass-card into a limited number (16) of directions and to represent the sum of all the dips attribu-

table to each direction by a line of appropriate length directed in the same sense. By doing so one gets a drawing called a diagram by the author. The diagram enables us to find by graphical or—more accurately—by arithmetical methods, figures characterizing the state of folding with respect to its intensity, direction, and uniformity. There is also shown the possibility of calculating the exactness of those figures, so that the tectonics of different areas may be compared in the same way as the features of organisms are compared in biometry.

The mathematical methods used by the author are rather simple ones which may easily be understood and used by every field-geologist interested in this kind of research. On the other hand, a more exhaustive treatment of the mathematical problems connected with the matter seems to be indispensable for further progress. No attempt has yet been made to utilize this system in regions more intensely disturbed, such as those of truly alpine character. It may be doubted whether it will be possible to do so.—*Author's Abstract.*

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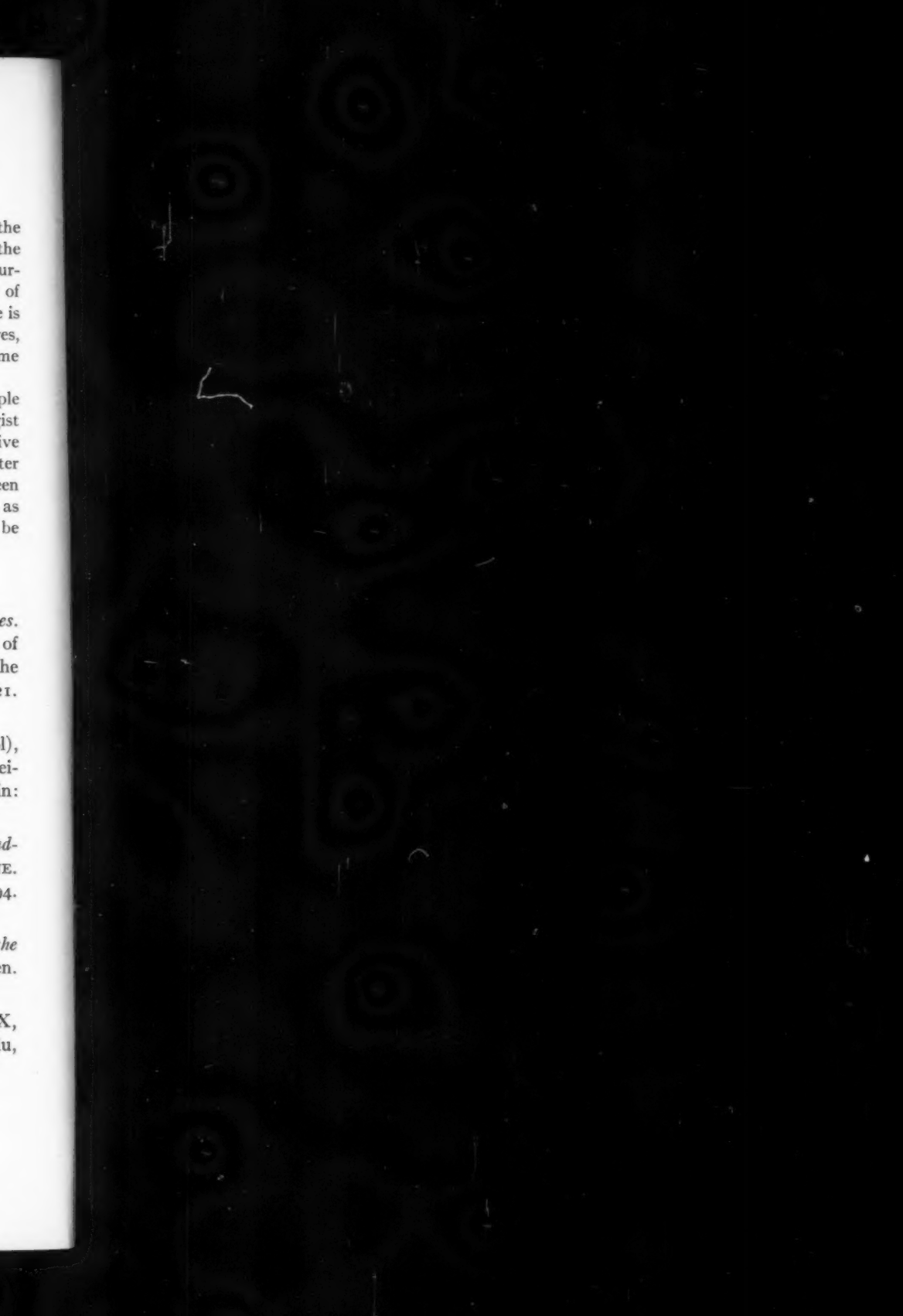
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